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On the rise and fall of oceanic islands: Towards a global theory following the pioneering studies of Charles Darwin and James Dwight Dana

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Abstract

The careers of Charles Darwin (1809–1882) and James Dwight Dana (1813–1895) are intimately linked to circumnavigations of the globe with the British mapping expedition on the H.M.S. *Beagle* (1831–1836) under Captain Robert FitzRoy and the United States Exploring Expedition (1838–1842) under Lieutenant Charles Wilkes. The former expedition mainly surveyed coastal South America, but also visited many volcanic islands in the Atlantic, Pacific, and Indian oceans. The latter expedition followed a similar path through the Atlantic, but devoted more time to Pacific Ocean islands. Remembered more today for his visit to the Galapagos Islands and its subsequent impact on understanding the mechanisms of biological evolution, Darwin was motivated early on during his stopover in the Cape Verde Islands to compile studies on the geology of volcanic islands. Better known for his theory of atoll development from the subsidence of volcanic islands stimulated by his visit to the Keeling Islands and published in 1842, Darwin also wrote a related volume published in 1844 with an equally strong emphasis on island uplift. Dana was influenced by Darwin's theory of atoll development, and published his own independent observations on coral reefs and island subsidence in 1843, 1849, and 1853. The work of both geologists matured from primary observations using inductive logic during fieldwork (i.g. unconformable position of limestone on and between basalt flows as an indicator of paleo-sea level) to the advancement of broader theories regarding the behavior of the Earth's oceanic crust. Notably, Dana recognized age differences among islands in Pacific archipelagos and was strongly influenced by the orientations of those island groups. The classic Hawaiian model that features a linear string of progressively older and subsiding islands does not apply easily to many other island groups such as the Galapagos, Azores, Canary, and Cape Verde islands. Geologists and coastal geomorphologists increasingly find that the original observations on island uplift covered in Darwin's, 1844 treatment provide an alternative pathway to understanding the complexities of island histories in oceanic settings. Original work by Darwin and Dana also led to ongoing studies on the trans-oceanic migrations of marine organisms, such as barnacles, corals and non-attached coralline red algae represented by rhodoliths. This work gives added importance to oceanic islands as way stations in the dispersal of biotas over time.

Keywords

- Oceanic islands;
- Carbonate deposits (rhodoliths and corals);
- Coastal geomorphology;
- Unconformities;
- Uplift;
- Subsidence

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1. Introduction

Research on oceanic islands that integrates coastal geomorphology, the physical styles of volcanic flows, and the paleontology of associated limestone or carbonate-rich deposits preserved between volcanic units (e.g. lava flows or pyroclastic deposits) had its beginnings with the observations of Charles Darwin during the voyage of the H.M.S. *Beagle* (December 1831 to October 1836). Barely three weeks out of Portsmouth, England at the start of the voyage, Darwin experienced stimulating intellectual ground on the island of Santiago in the Cape Verde archipelago. Testing his abilities as a geologist in the countryside around the provincial capital of Praia, the young naturalist quickly found confidence that he might produce a book based on his experiences during the overall voyage (Barlow, 1958; Pearson and Nicholas, 2007). A parallel sense of adventure and self-assurance came to the American geologist James Dwight Dana, who participated in a circumnavigation of the globe with the United States Exploring Expedition

(August/September 1838 to June 1842) serving on the U.S.N.S. *Peacock* and *Vincennes* during which many volcanic islands in the Pacific Ocean were visited and studied. Together, the pioneering studies by Darwin, 1839; Darwin, 1842 ; Darwin, 1844 and Dana, 1843; Dana, 1849; Dana, 1853 ; Dana, 1890 provide insights on early thinking regarding the tectonics of ocean basins (Dott Jr, 1997) and the geological history of oceanic islands in terms of contrasting patterns of subsidence and uplift (Woodroffe, 2014). The narratives compiled by these early explorers remain fresh both for their remarkable acuity, but also for their broad embrace of natural history in the context of physical geography, whereas today the sub-disciplines of field biology and field geology have become increasingly specialized. As members of shipboard communities working under sail, both Darwin and Dana were sensitive to the prevailing winds and wind-driven waves that influenced local patterns of erosion and deposition around the islands on their respective itineraries. Their remarks on limestone deposits, volcanic eruptions and styles of basalt flows, as well as island geomorphology make for comparisons that give insight to development of a more integrated outlook on the geology of oceanic realms.

The several goals of this survey are to: 1) review the most salient observations made independently by Darwin and Dana during their visits to islands in archipelagos scattered through the Atlantic, Pacific, and Indian oceans, 2) augment and update those observations based on subsequent studies by geologists who visited the same islands or related islands in the same archipelagos with particular attention to unconformities that reflect paleoshores including marker beds formed by limestone, 3) relate differing patterns in the origin, distribution, and demise of oceanic islands to current thinking on global tectonics, 4) reconsider variations in island limestone composition in terms of regional differences more favorable to coralline red algae and related rhodoliths as opposed to coral reefs, and 5) address issues of inter-regional migration of marine invertebrates along island stepping stones using examples of studies launched by Darwin and Dana.

1.1. Oceanic Islands and plate tectonics

Excluding volcanic island arcs such as the Lesser Antilles, the Aleutians and the islands of Japan that form behind subduction-zone trenches, the vast majority of oceanic islands are related to intra-plate hotspots (e.g. Zaczek et al., 2015). Stationary hotspots entail magmatic plumes that rise to provide excess heat to the upper mantle and drive partial melting. In turn, partial melting feeds magma through the Earth's outer crust to erupt at the seafloor, giving rise to sea mounts, emergent islands, and subaerial shield volcanoes. Most of the world's roughly 49 hotspots are situated below mobile oceanic crust, although some occur below thicker continental crust, as for example the Yellowstone hotspot (Courtillot et al., 2003). Hotspots are sometimes inter-act with spreading centers between tectonic plates, as for example below Iceland between the divergent North American and Eurasian plates or in the Azores between the North American, Eurasian, and African (Nubian) plates. Table 1 provides a summary of the world's oceanic islands classified according to the principal tectonic plates and associated hotspots.

Table 1.

Distribution and number of oceanic islands belonging to the Earth's main tectonic plates (organized after Menard, 1986).

Tectonic Plate	Average speed (cm/yr)	Active oceanic volcanoes	High islands	Atolls	Total oceanic islands and atolls
North America	2.5	0	3	0	3
South America	2	0	4	1	5
Eurasia (Atlantic)	1	0	7	0	7
Africa (Atlantic)	2	3	30	0	30
Somali	0.45	1	2	0	2
India-Australia	6	0	181	72	253
Pacific	10	10	198	94	292
Philippine/Mariana	0.5	0	15	0	15
Nazca	6	3	24	0	24
Cocos	6	0	1	0	1
Antarctic	1	0	5	0	5

Table options

From this summary (Table 1), it is clear that the Pacific Plate encompasses more historically active volcanoes and a greater concentration of atolls compared to any other plate. This is not surprising, due to the size of the Pacific Plate and its comparatively long oceanic history. Some of the oldest guyots on the Pacific Plate represent sunken islands that occur near the terminus of the Hawaii-Emperor chain of islands and seamounts off northern Japan with an age correlative to the Late Cretaceous at 75.8 Ma (Clouard and Bonneville, 2005). This is significant for the present paper, because aspects of plate dynamics in the Pacific Ocean are markedly different from the Atlantic Ocean.

2. Historical background

2.1. Darwin and Dana

Global trade routes first established by the Portuguese and the Spanish during the Age of Discovery in the fifteenth and sixteenth centuries set the stage for European explorations of oceanic islands and laid the basis for a truly global geography (Leitão and Alvarez, 2011). The British Admiralty's compilation of navigational charts was advanced during the nineteenth century with three voyages by the H.M.S *Beagle,* the most famous of which occurred under the command of Captain Robert FitzRoy from 1831 to 1836. Charles Darwin (1809–1882) was enlisted as a gentleman companion to Captain FitzRoy, paying from family resources to attend the expedition as a private citizen. Americans entered the scene under the aegis of the United States Exploring Expedition (1838–1842) with Lieutenant Charles Wilkes in command of several vessels including the refitted war sloops U.S.N.S. *Vincennes* and *Peacock*. James Dwight Dana (1813–1895) was one of several naturalists formally engaged in the expedition to provide scientific expertise across a broad range of subjects. The principal missions entrusted to FitzRoy and Wilkes were those of chart making. Hence, the naturalists under their authority were given access to particular islands for only limited periods of time strictly in accordance with the most expedient charting schedule.

The academic preparations of Darwin (Fig. 1) and Dana (Fig. 2) were different going into their unofficial and official duties. Given the end products of their work, however, it is clear they became the first geologists to make direct and detailed observations on a host of oceanic islands spread widely around the world. Darwin had no formal training in geology beyond a brief apprenticeship as an assistant to the Cambridge University geologist Adam Sedgwick prior to the *Beagle*'s departure from Plymouth at the end of the year in 1831 (Herbert, 2005). Desiring a companion conversant in geology, it was Captain FitzRoy who made a present to Darwin of Volume I of *Principles of Geology* by Charles Lyell (Pearson and Nicholas, 2007). Soon enough, Lyell became Darwin's geology mentor in absentia. In contrast, Dana studied geology under Benjamin Silliman at Yale College in New Haven and then obtained a position as a mathematics instructor to midshipmen in the U.S. Navy on duty in the Mediterranean. In 1834, Dana climbed the Italian volcano Vesuvius and his observations were published in Silliman's *American Journal of Science*. Returning to Yale, Dana published his first book *A System of Mineralogy* in 1837. Thus, by the time Dana embarked on the U.S.N.S. *Peacock* at Hampton Roads as a member of the U.S. exploring expedition in September 1838, he was already a published geologist with a proven expertise.

Fig. 1.

Portrait of Charles Darwin at age 31 in 1840 by George Richmond.

Figure options

Fig. 2.

Portrait of James D. Dana at age 50 in 1863, artist unknown.

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Darwin and Dana were separated in age by only four years and Darwin's voyage on the *Beagle* ended almost two years before Dana set out on the first stage of his voyage on the *Peacock*. Both geologists left home for nearly five years. The maps in Fig. 3 ; Fig. 4 plot the respective itineraries of the *Beagle* and the *Peacock*/*Vincennes.* Using ship's logs and the published records left by the principals (Darwin, 1839 ; Darwin, 1844; Dana, 1843; Dana, 1849 ; Dana, 1853), the places visited and the degree of overlap in their investigations can be compared. In the North Atlantic, both stopped off on St. Jago (Santiago) in the Cape Verde islands, but Dana had little to say. Darwin had occasion to visit the island twice, first at the start of the voyage during a stay of 24 days (during which the several chronometers carried by the *Beagle* were calibrated) and towards the conclusion of the voyage for a stay of five days on the return to England. Dana recorded useful notes regarding fossil corals from Madeira, which Darwin had no opportunity to visit. Dana's most extensive body of research covered the Hawaiian Islands (big island of Hawaii, Oahu, and Kauai), which Darwin never visited. Dana had occasion to return to Hawaii twice during the expedition, and for a third time later on in life. The only overlap between the two geologists in the Pacific Ocean was Tahiti. The only atolls visited by Darwin were in the Cocos (Keeling) Islands in the Indian Ocean. Dana had occasion to witness many atolls in the Gilbert Islands during a stay of 28 days and in the Marshall Islands (8 days). Darwin's commentary on the Galapagos Islands is extensive, whereas Dana had no opportunity to visit those islands.

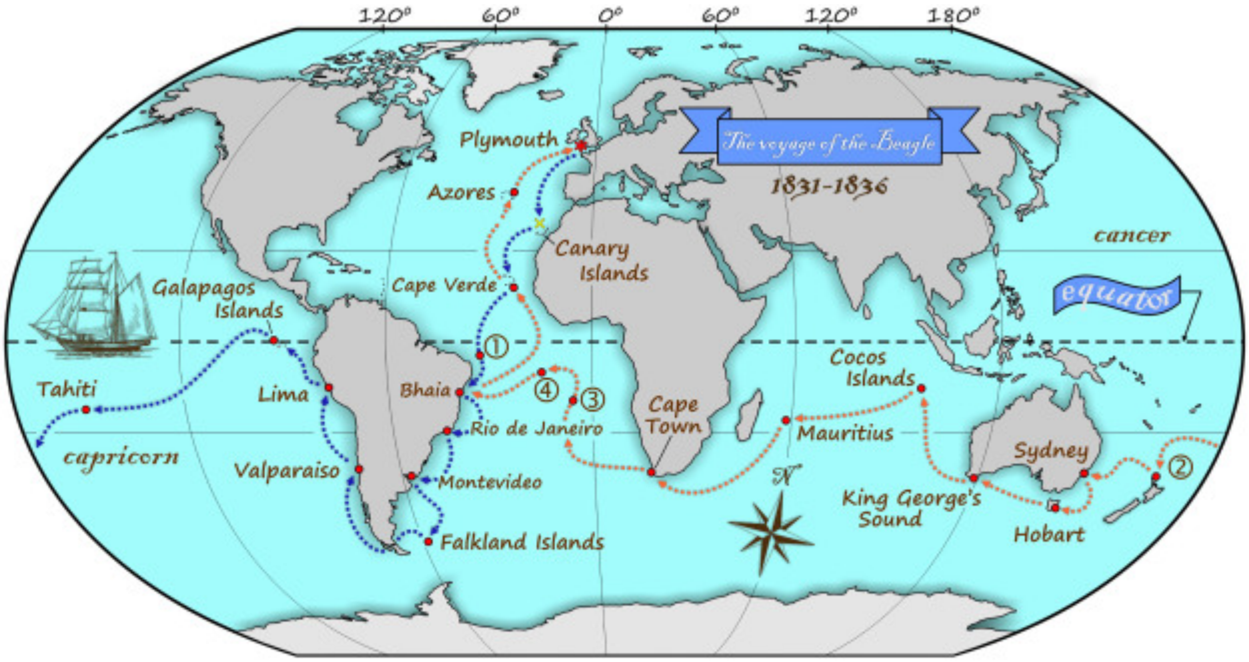

Fig. 3.

Circumnavigation of the globe (1831–1836) attended by Charles Darwin on the HMS *Beagle* with selected stopping places denoted by number on the outward- bound voyage (1 Fernando de Noronha) and homeward bound voyage (2 New Zealand, 3 St. Helena, and 4 Ascension Island).

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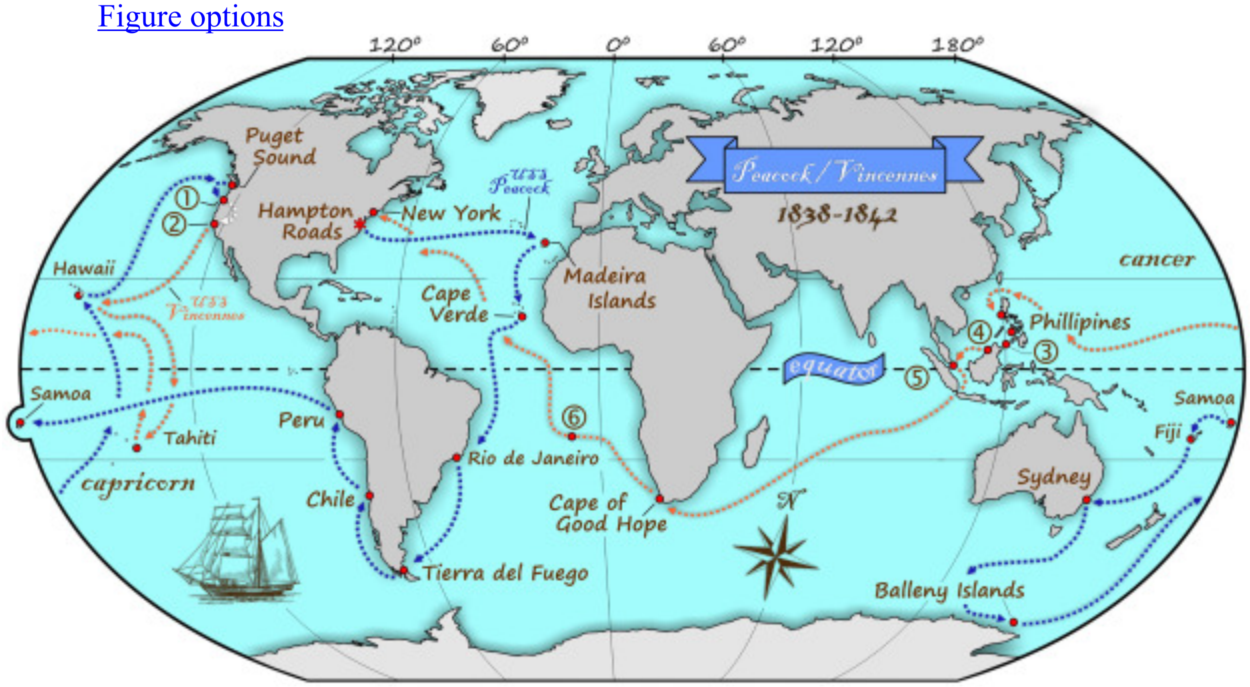

Fig. 4.

Circumnavigation of the globe (1838–1842) by the USSN *Peacock* (path in blue) and *Vincennes* (path in brown) attended by James D. Dana, marking the sinking of the *Peacock* (1 off the mouth of the Columbia River) and selected stopping places of the *Vincennes* (2 San Francisco, 3 Sulu Islands, 4 Borneo, 5 Singapore, and 6 St. Helena). Note that the Tuamuto Archipelago, where no actual landings were made from the *Peacock*, is located east of Tahiit.

Figure options

The following vignettes on specific islands visited by Darwin and Dana are not ordered by the strict chronology of those visits, but are divided into two groups consisting of volcanic islands with open shelves unprotected by coral reefs as opposed to those sheltered by fringing coral reefs, barrier reefs, or reefs built around atolls. However, the summaries progress through the North Atlantic, South Atlantic, East Pacific, South Pacific, North Pacific, and Indian oceans in much the same orderly fashion cruised by the separate expeditions during their global circumnavigations. Dana landed in Madeira at the start of his travels, but otherwise spent little time in the Atlantic Ocean. Darwin had much less exposure to islands in the Pacific Ocean, but had the opportunity to visit additional Atlantic islands towards the end of his voyage, not seen earlier. Commentary appended to each of the vignettes highlights the work by later geologists who added to the literature on reef rudstone and non-reef limestone from the same islands or other islands in the same archipelagos with particular emphasis on tectonic uplift or subsidence.

3. Volcanic Islands unprotected by coral reefs

3.1. Cape Verde archipelago

HRS *Beagle* set anchor in Praia harbor on Santiago Island on January 16, 1831. Exploring "Quail Island" (officially Santa Maria Islet) within the harbor district, Darwin was fascinated by coastal cliffs with a tri-part sequence of white limestone sandwiched between basalt flows. He was able to trace these beds eastward over a distance of 10 km to Ponta das Bicudas and northwards to Facho (Fig. 5). The maximum 6-m thick limestone layer features abundant calcareous concretions that he identified as "Nulliporae" (coralline red algae), as well as copious erosional detritus likened to "mortar" (Darwin, 1844 p. 4). In this instance, Darwin was the earliest commentator to consider the role of rhodoliths in building substantial limestone formations (Fig. 6 ; Fig. 7). The Pleistocene limestone also incorporates other fossils, such as oysters and limpets of an intertidal nature, and he was the first to describe such deposits in the context of former rocky shores. In quite another context, Darwin eventually came to understand the limestone marker beds in a "uniformitarian" light with regard to changes in relative sea level caused by uplift and subsidence, as advocated by Charles Lyell. According to Pearson and Nicholas (2007), Darwin had not yet read Lyell during the three weeks that had elapsed since his departure from England and his first arrival to Santiago Island.

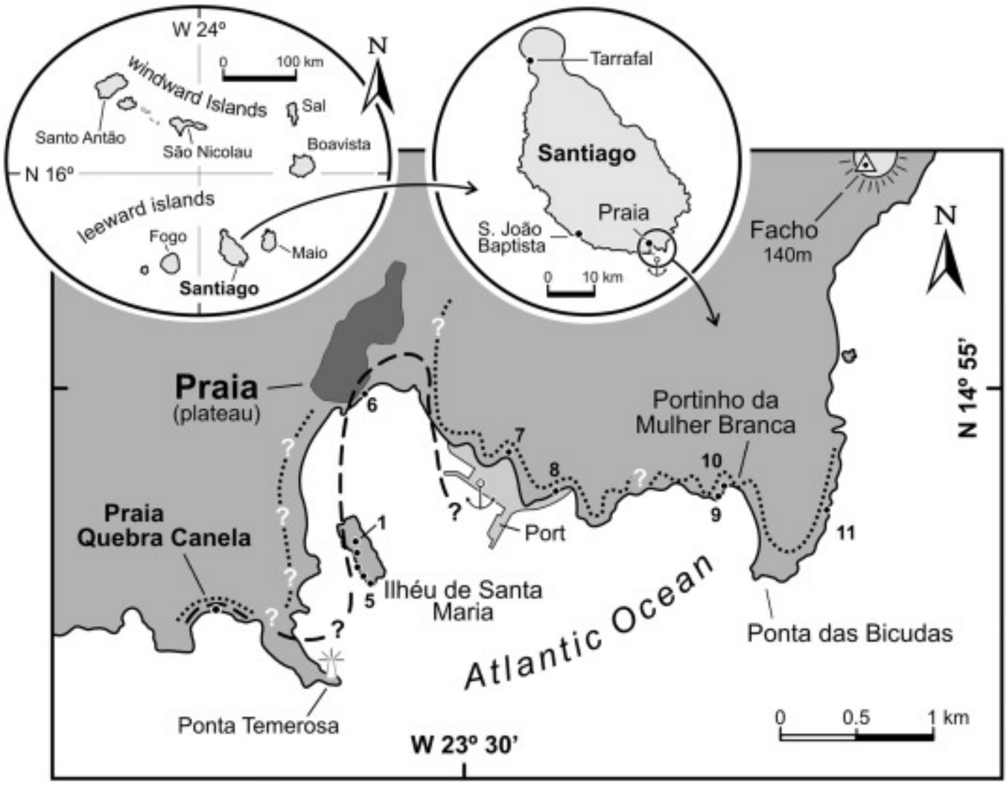

Fig. 5.

Maps showing the Cape Verde Islands with enlargement of Santiago Island and details of the coastal area around Praia on the southeast coast of Santiago visited by Darwin in 1831 and 1836. Dashed lines follow the trace of two distinct paleoshores of Pleistocene age. Numbers mark localities for stratigraphic sections described by Johnson et al. (2012).

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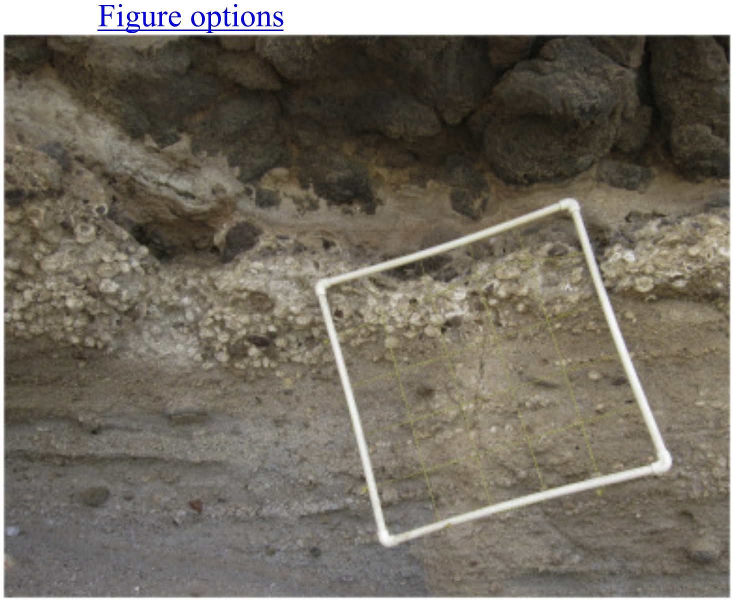

Fig. 6.

Rhodolith limestone exposed on the west shore of Ilhéu de Santa Maria in Praia harbor, known to Darwin as Quail Island. The grid used for scale measures 50 cm by 50 cm (see Johnson et al., 2012 for details).

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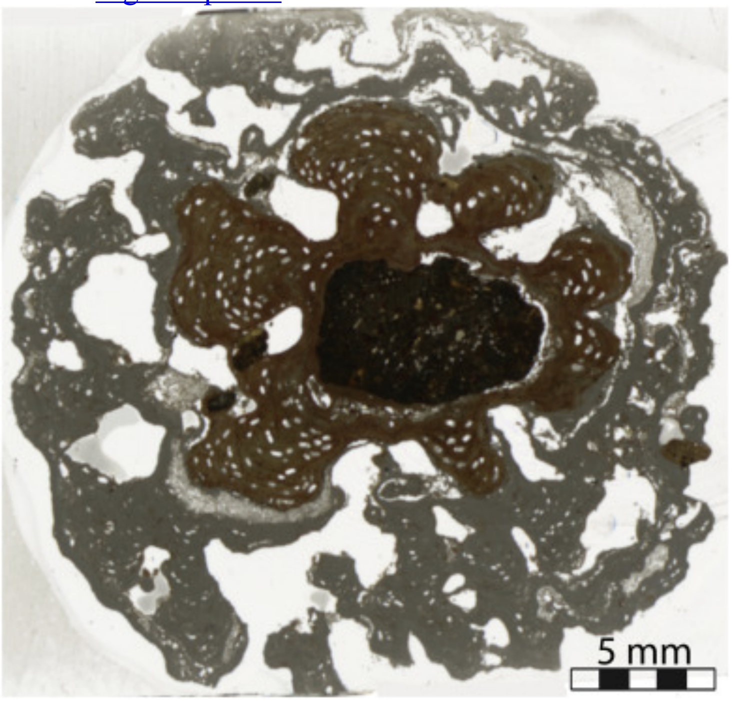

Fig. 7.

Cross section of a rhodolith 2.5 cm in diameter encrusted around a basalt pebble (black), from Ilhéu de Santa Maria. The two tones (brown and gray) represent a change over from one kind of coralline red algae to another. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure options

Johnson et al. (2012) retraced Darwin's footsteps on Santiago and logged 11 stratigraphic profiles through limestone deposits to show variations in thickness, content, and lateral differences in contacts with underlying and overlying basalt. Based on these variations, it later was concluded that not one, but two distinct limestone bands were deposited against the island's flank during different stages in the vertical rise and fall of the island. Subsequent exploration as far as Praia de Quebra Canela to the west (Fig. 5) confirmed the presence of two distinct limestone marker beds one above the other (Fig. 8). Explorations near Ponta das Bicudas also revealed fossil coral heads directly attached to basalt basement rocks in a small quarry that was excavated sometime after Darwin's visits to the island (Baarli et al., 2013). The site not only reinforces Darwin's original interpretation of coastal deposits, but it also represents a rare variation with corals having grown in place under very high-energy conditions antecedent to actual reef formation.

Fig. 8.

Quebra Canelas Beach in Praia on Santiago Island with dashed lines (white) marking the levels of two distinct paleoshores represented by unconformities between Pleistocene rhodolith limestone and underlying basalt.

Figure options

Leaving Santiago on February 8, 1832, the *Beagle* sailed southwest towards Brazil. São Nicolau is one of the archipelago's windward islands, located more to the northwest where a limestone marker bed is prominently exposed on the coast between underlying and overlying basalt flows (Fig. 9 ; Fig. 10). The age of this limestone is Late Miocene (Johnson et al., 2014) and it contains extensive rhodolith debris. Were Darwin allowed more time for exploration among the Cape Verde Islands and were he more cognizant of Lyell's outlook on geology at that time, Darwin would have been intrigued to find another example of an island's response to relative changes in sea level.

Fig. 9.

Miocene rhodolith limestone (white band) along the southeast shores of São Nicolau in the Cape Verde Islands as viewed from the air. The limestone is bracketed above and below by basalt flows.

Figure options

Fig. 10.

Ground view of the Miocene rhodolith limestone on the southern shore of São Nicolau.

(See Johnson et al., 2014 for details).

Figure options

3.2. Azores archipelago

The last landfall before the *Beagle* returned home to England was at Angra (now Angra do Heroísmo) on Ilha da Terceira from September 19 to 22, 1836 (Fig. 3). Darwin (1844) described the prominent tuff cone of Mount Brazil, which projects outward from the islands' south-central coast to form one side of the town's harbor, and he drew a direct comparison with the young cratered hills widespread in the Galapagos islands. Surtseyan tuff expelled from this volcano caps older ignimbrite cliffs on which the town is seated, now known to be about 23,000 years old (Self, 1976). The tuff itself is considered to be Holocene in age. Much of Darwin's commentary is devoted to the interior of Terceira, where he visited active fumaroles. There, he imagined that a volcanic plug similar to the high peak on the main island of Fernando de Noronha (see below) lay concealed below the center of Terceira, where rainwater would percolate downwards to be heated against a hot core (Darwin, 1844 p. 25). In terms of relative age, his comparison is apt, because Terceira is a very young volcanic landscape as opposed to Fernando de Noronha, where insufficient time had elapsed to fully exhume its volcanic plug.

Seeking mail, the *Beagle*'s crew sent a boat ashore to Ponta Delgada on São Miguel, pausing offshore only briefly on September 23, 1836. Darwin (1844) recorded nothing on the volcanic landscape of this island. Had the *Beagle* sailed another 65 nautical miles southeast to the island of Santa Maria, the easternmost island in the Azores, Darwin would have witnessed the only substantial limestone formations exposed in the entire archipelago. Today, several localities that are rich in fossiliferous deposits are under formal protection as geosites inside the UNESCO Global Geopark Azores and Palaeopark Santa Maria (Nunes et al., 2010; Ávila et al., 2014). A comprehensive overview of these deposits that range from the lower Pliocene into the Pleistocene is provided by Ávila *et al*., 2018a ; Ávila *et al*., 2018b. Similar to Darwin's earliest experience on Santiago in the Cape Verde islands, Pliocene limestone with abundant rhodoliths are found at Malbusca (Rebelo et al., 2014; Rebelo et al., 2016) on the southeast coast of Santa Maria Island (Fig. 11). Succeeding the basal rhodolith limestone are layers that feature shell beds and mixed volcaniclastic-calcarenite sandstone that are bracketed above and below by basalt. Throughout 5-m thick volcaniclastic-calcarenite sandstone at Malbusca, distinctive lamina form alternating dark (pyroxene-rich) and white (shell-rich) components that are interpreted as a hurricane deposit (Johnson et al., 2017a). Nearby Malbusca at Pedra-que-Pica, more Pliocene limestone, rich in fossil pectenids, occurs off a former rocky shore on a wave-cut shelf eroded in basalt (Ávila et al., 2015).

Fig. 11.

Malbusca on the southern coast of Santa Maria Island in the Azores, showing upper Miocene to lower Pliocene limestone that includes abundant rhodoliths.

Figure options

3.3. Fernando de Noronha Archipelago (South Atlantic Ocean)

A single day, February 20, 1832, was allotted for the *Beagle*'s landing party to visit the principal island of Fernando de Noronha 354 km off the coast of Brazil (see Fig. 3, locality 4). With the ship anchored off Praia da Atalaia on the windward side of the island (Fig. 12), the landing occurred under rough conditions. Darwin (1844) had little to say about the geology, noting that weathered columns of basalt were exposed near the landing place and that the island's highest peak consisted of "columnar phonolite." Dedicated in 2001, the archipelago is today a UNESCO World Heritage Site. Detailed guidebooks cover all aspects of the island's natural history, as for example by Teixeira et al. (2003). The peak described by Darwin is Morro do Pico overlooking the north shore (Fig. 13). It represents the eroded remains of a volcanic plug assigned to the Miocene-Pliocene Remédios Formation. Tuffs and basaltic flows near the coast visited by Darwin correlate with the Pliocene-Pleistocene Quixaba Formation.

Fig. 12.

Atalaia Bay on the main island of Fernando de Noronha visited by the *Beagle* in 1832.

Figure options

Fig. 13.

Morro do Pico on the north shore of Fernando de Noronha, representing a volcanic plug described by Darwin as formed by columnar phonolite.

Figure options

Sedimentary rocks consisting of Pleistocene carbonate dunes, as exposed at Ponta Caracas, are limited mainly to bays on the south side of the island. Had Darwin been allowed more time to explore these shores, he surely would have found sedimentary deposits of cross-bedded dune rocks now assigned to the Caracas Formation that sit on basal conglomerate derived from the underlying volcanic Quixaba Formation. The dune rocks are composed of bioclastic fragments (Teixeira et al., 2003). A study on modern rhodolith beds around Fernando de Noronha by Amado-Filho et al. (2012a) shows that crustose coralline algae are the primary carbonate producers with accumulations accruing at depths from 10 to 100 m. Given the opportunity to walk the shores of the main island, Darwin might have picked up modern rhodoliths much as he had observed as fossils on Santiago in the Cape Verde Islands. He also might have noted that a component of the fossil dune rocks on Fernando de Noronha consists of crushed rhodoliths.

Departing Fernando de Noronha late on February 20, 1832, it would take more than four years before Darwin would see his first coral atolls in the Cocos (Keeling) Islands of the Indian Ocean (see Fig. 3). As it was, the *Beagle* passed south of the Atol das Rocas located about 110 km east of Fernando de Noronha on the track of the Fernando de Noronha's hotspot, one of the few hotspots attributed to the impingement of a mantle plume below the South American Plate. The rim of Atol das Rocas is built exclusively of coralline red algae (Gherardi and Bosence, 2001). Sediment from the debris of crustose coralline algae covers the atoll's lagoon at a maximum water depth of 5 m. Thus, the make-up of this South Atlantic atoll is fundamentally different from the Indian and South Pacific atolls that Darwin (1842) later wrote about.

3.4. Ascension Island (South Atlantic Ocean)

The British garrison was a stopping place from July 19 to July 23, 1836 on the *Beagle*'s return voyage to England (Fig. 3). Geological notes by Darwin (1844 p. 35) include observations on a multitude of “conical, red-coloured hills, which are scattered over the northern and western borders of the island” and from which individual outflows of basalt are traceable as the source. The volume's frontispiece presents a detailed map of the island showing this landscape (Fig. 14). Darwin found that the summits of many craters were “cut off obliquely, and they all sloped towards the S.E., whence the trade-wind blows.” Together with the observation that volcanic tuff is most extensive on the leeward side of the island, Darwin concluded that scoria and ash from these secondary cones were often carried down-wind under the influence of the prevailing winds.

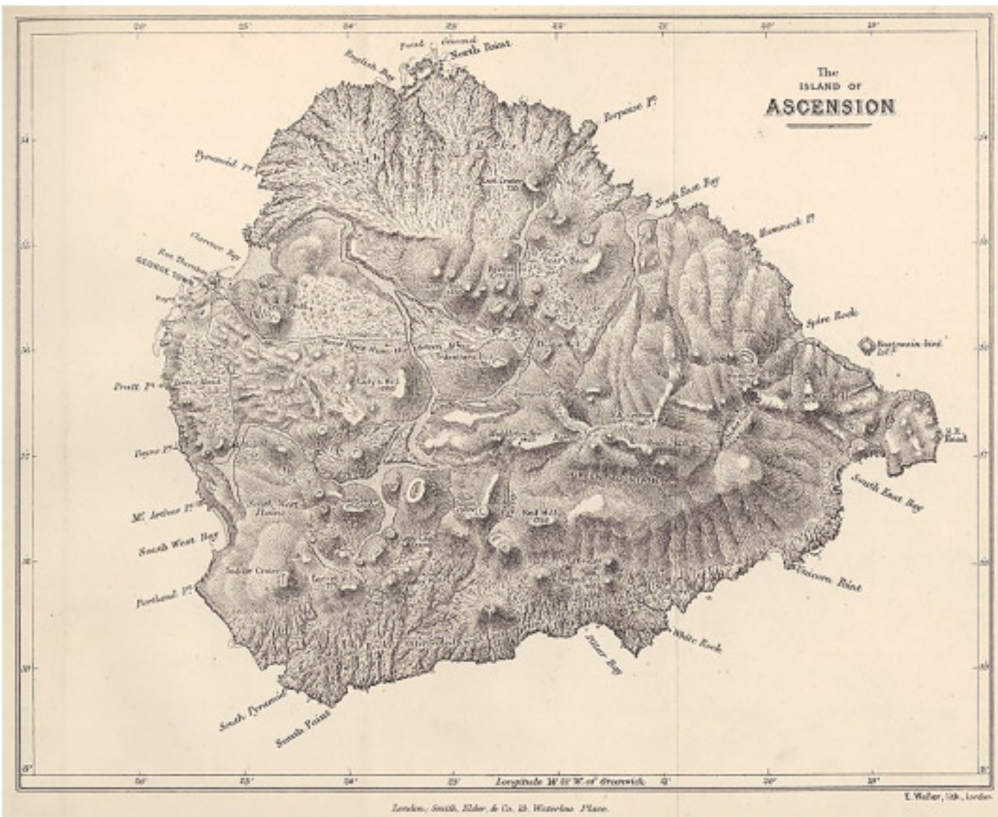

Fig. 14.

Map of Ascension Island used as the frontispiece of Darwin's volume on volcanic islands.

(Darwin, 1844)

Figure options

Among all the oceanic islands described by Darwin (1844), Ascension is unusual for fragments of medium-gained syenite embedded as xenoliths within chunks of scoria. These felsic rocks, in addition to surface flows of rhyolite were confirmed and mapped in detail by Nielson and Sibbett (1996), who invoke fractional crystallization in a stratified magma chamber as the source during the later stages of the island's volcanic history. The synthesis by Van Andel et al. (1973) on Ascension Island and the geophysics of the nearby Ascension Fracture Zone across the Mid-

Atlantic Ridge provide no evidence that the seven-million-year-old island is associated with a hot-spot chain of island volcanoes, but is more isolated in its placement.

Darwin (1844 p. 49) described the “formation of calcareous rocks on the sea-coast” at various beaches around Ascension Island that conform to what nowadays is called beach rock. He reported that the deposits consist of “immense accumulations of small, well-rounded particles of shells and corals, of white, yellowish, and pink colours, interspersed with a few volcanic particles” becoming solid rock at depth. Intriguingly, Darwin also quoted a local source on changes in calcareous coatings up to “half-an-inch in thickness” on tidal rocks near the settlement apparently caused by seasonal variations in the environmental setting. This phenomenon and related coatings of “frondescent calcareous incrustations” on tidal exposures of volcanic rocks (Darwin, 1844 figure No. 5, p. 51) have yet to be reconciled with modern science. It is noteworthy, however, that present-day surveys of the shallow subtidal zone around Ascension Island reveal high concentrations of rhodoliths and attached “towers” of coralline red algae growing on rocks in great profusion (Fig. 15). Corals are absent. A significant volume of beach rock may have derived from the abraded remains of rhodoliths. Moreover, the coatings described by Darwin may have been due to encrustations by calcareous red algae.

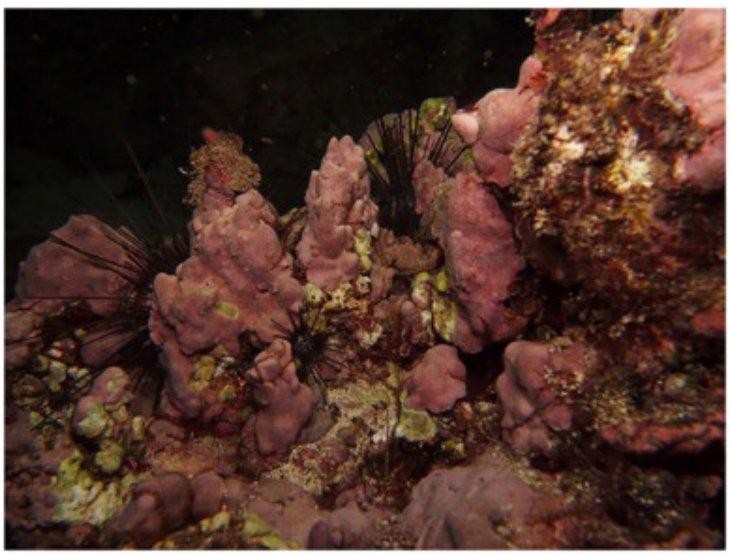

Fig. 15.

Coralline red algae towers in English Bay, Ascension Island. Photo credit: F. Kuepper and K. Tsiamis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure options

3.5. St. Helena Island (South Atlantic Ocean)

Prior to reaching Ascension Island on its homeward journey, the *Beagle* was re-provisioned at St. Helena from July 8 to 14, 1836. Darwin (1844) compiled extensive geological notes during his relatively short stay. He reported that high, basaltic sea cliffs (rising vertically by as much as

2000 ft or 600 m in height) dominate much the island's 28-mile (45-km) circumference. Within this cliff sequence, he differentiated a lower set of flows exposed near sea level said to intercalate with scoria and laminated tuff bearing rounded pebbles. These beds also were said to include a quantity of gypsum and salt. Darwin (1844 p. 75) took this as evidence that the older (basal) "volcanic strata flowed beneath the sea" and that such features being absent from subsequent flows implied island uplift. Daly (1927) found no differences between older and younger basalt flows that dip at angles from 5° to 15° seaward from the highest points on the island as a composite volcanic cone. He reconfirmed, however, the weathered remains of three phonolitic plugs in the island's central valley, an igneous rock Darwin correctly associated with the same hillocks. The exposed subaerial history of the island between about 14 to 7 Ma was established by Baker (1969).

A break in slope on the surrounding insular shelf occurs near the 50-fathom isobath at a distance from 1.3 km to 3.0 km from the shore, as cited by Daley (1927 p. 34) in affirmation of Darwin's general argument for extensive coastal erosion around the island. It is most relevant to the description by Darwin (1844 p. 86) regarding calcareous sandstone left as superficial deposits up to 15 ft (4.5 m) thick in valleys on the north and south sides of St. Helena at elevations "between six hundred and seven hundred feet [~183 to 213 m] above the sea." Darwin ascribed these cemented deposits to the accumulation of wind-blown bioclasts, well sorted and well rounded, derived from marine shells and other organic bodies that retain traces of original coloration. Although no identifiable shell fragments were recovered, he attributed the deposits to deflation of shelly beach sands by the prevailing trade winds long before the island acquired its high coastal cliffs. He also opined that the present heights of the deposits could be "due to an elevation of the land, subsequent to the accumulation of the calcareous sand" (Darwin, 1844 p. 87). Some layers exposed in a quarry at Sugar-Loaf Hill were found by Darwin to include terrestrial gastropods, which supports the interpretation of island sand dunes. Overall, the concentration of calcium carbonate materials in these sand bodies was said to be on the order of 70%.

In this specific case, Darwin's original observations relate to deposits that clearly are aeolian in nature. Olsen (1975), reviewed later studies on calcareous sand in the vicinity of Sugarloaf Hill with the conclusion that the material was derived from the shells of marine invertebrates blown inland from a former beach during a low-stand in sea level exclusive of the 5-m raised beach that surrounds the island today. To the best of our knowledge, no petrographic analysis of the dune sands has been conducted to verify the presence or absence of bioclasts derived from coralline red algae. Other volcanic islands in the North Atlantic Ocean, such as Maio and São Nicolau in the Cape Verde archipelago and Porto Santo in the Madeira archipelago, feature Pleistocene sand dunes with extensive carbonate materials derived from rhodoliths (see Appendix 1 for listings).

3.6. Galápagos Islands (East Pacific Ocean)

The *Beagle* anchored off Chatham Island (San Cristobal) on September 16, 1835 and departed from the archipelago 35 days later on October 20 from a position between the outlying islets of Wentman (Wolf) and Culpepper (Darwin). Darwin spent time ashore on four of the archipelago's 18 islands and gathered information and geological specimens from crewmembers who visited several others. Almost immediately after setting foot on Chatham at Frigatebird Hill, Darwin

(1844 p. 114–115) found evidence in support of coastal uplift shown by “blocks of lava cemented by calcareous matter containing recent shells” lodged some distance above the tide line. The comment appears under a heading titled “Elevation of the Land.” Although he remained vigilant in the search for additional examples of island uplift in the Galápagos Islands, Darwin's itinerary failed to bring him to other places that afforded better evidence (Johnson and Baarli, 2015).

Meanwhile, other findings relevant to geology were registered as the *Beagle* cruised the islands. One of the more insightful observations confirmed by crewmembers near James Island (Santiago) in the Bainbridge Group of islets (Fig. 16) relates to the coastal geomorphology of tuff cones with reduced or entirely breeched walls open to the south. Darwin (1844 p. 113) registered this pattern of erosion on 28 tuff cones, directly attributed to the action of “waves from the trade-wind, and the swell propagated from the distant parts of the open ocean –with their united forces [that] attack the southern sides of all the islands.” On James Island (Santiago), where Darwin spent the longest time ashore on any island in the archipelago and visited the island's summit crater, a novel observation was advanced regarding magmatic differentiation of igneous rocks by the process recognized, today, as crystal fractionation. Re-examination of the locality in 2007 reconfirmed Darwin's original field observations (Herbert et al., 2009).

Fig. 16.

Breached tuff cones from the Brainbridge Group in the Galápagos Islands, which Darwin observed to be preferentially eroded on the southeast sides.

Figure options

Limestone strata without fossil corals bracketed by basalt flows similar to the sort observed previously in the Cape Verde Islands by Darwin also occur in the Galapagos Islands (Johnson and Baarli, 2015). It was a matter of bad luck that Darwin's itinerary missed the 1.5-km wide strait between North Seymour and Baltra islands in the central part of the archipelago, but the *Beagle* passed nearby along the outer shores of North Seymour for survey work when Darwin was not aboard. Hickman and Lipps (1985) and a more detailed review by García-Talavera

(1993) cover the most important fossil localities in the Galápagos Islands, including the sea cliff on the north shores of Baltra Island where a Pliocene marine fossil assemblage of 30 gastropods, and nine bivalve species contributes to a limestone layer conformable with a channelized basal conglomerate containing basalt cobbles eroded from the underlying basement. The transition zone between pillow basalt and columnar basalt that marks the start of a subaerial flow occurs 12 m above the top of the limestone (Fig. 17). Assuming a conformable contact between the top of the sediments and the overlying submarine lava flows, the relationship suggests the limestone was deposited in water about 12 m deep. A stratigraphic profile with the same succession of units is found in sea cliffs on North Seymour Island along the opposite side of the strait (Fig. 18). Correlation of these strata demonstrates that a sizable area was uplifted by roughly 12 m in post-Pliocene time.

Fig. 17.

Uplifted Pliocene limestone bracketed by basalt flows on the north shore of Baltra in the Galápagos Islands.

Figure options

Fig. 18.

Uplifted Pliocene limestone bracketed by basalt flows on the south shore of North Seymour in the Galápagos Islands.

Figure options

Another example of local uplift that features a thin limestone marker bed comes from Isla Sombrero Chino, a volcanic islet off the southeast coast of James Island (Santiago). As the pristine volcanic cone on the island has an age 13,000 years, the elevated limestone deposit must be younger. The relationships were discovered in 2009 during a course-related field excursion to the Galápagos Islands from Williams College (Johnson et al., 2010), which shows that new discoveries can be made even in high-traffic areas frequented by tourists. The limestone is composed of abundant intertidal gastropods, detached spines of echinoids, and rare pieces of bird bones.

4. Volcanic Islands sheltered by coral reefs

4.1. Madeira archipelago (North Atlantic Ocean)

During the first landfall of his voyage at Funchal on Madeira, Dana (1843 p. 555) witnessed the unloading of "large quantities of coral limestone, which had been brought from small islets near Porto Santo." This material was processed as slaked lime used as whitewash and mortar for buildings on the big island of Madeira and it was mined from an extensive network of underground excavations on Ilhéu de Baixo off Porto Santo. The actual source was probably the Blandy Brothers mine, where high quality lime rock represented by calcarenite with a major component of rhodolith debris is stratigraphically overlain by coarse rudstone dominated by the coral *Pocillopora madreporacea* (Baarli et al., 2014). These corals (Fig. 19) date to about 15 Ma from the Middle Miocene. Together with related sedimentary strata, the corals are part of a debris flow bracketed by basaltic rocks. Fossil-bearing beds now are exposed 50 m above sea level. Evidence suggests that a former coral reef was in place on Ilhéu de Baixo prior to its collapse. The main island of Madeira also records the development of Miocene reef-forming limestones at Cargo do Barrinho (Ramalho et al., 2015). Had Dana gone out to Porto Santo and visited another islet associated with that island (Ilhéu de Cima), he would have encountered limestone dominated by Miocene rhodoliths (Fig. 20) also bracketed by basaltic rocks. The massive rhodolith deposit at Cabeço das Laranjas (Hill of Oranges) on Ilhéu de Cima is interpreted as a result of major storms (Johnson et al., 2011).

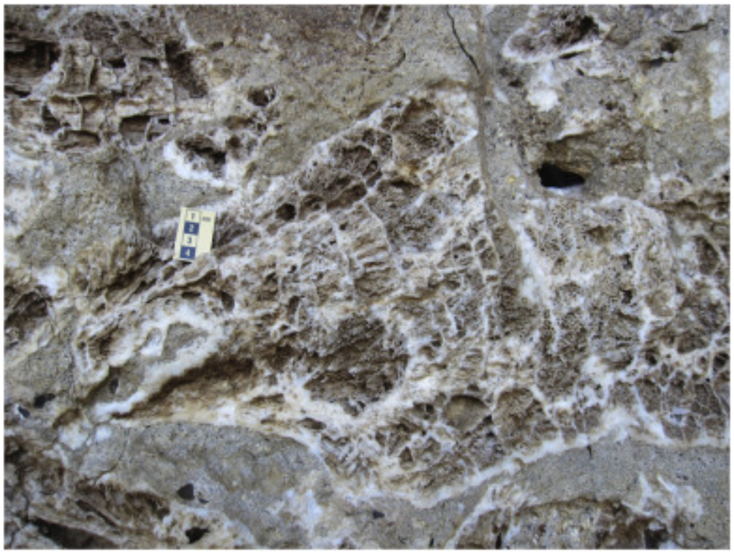

Fig. 19.

Miocene coral limestone dominated by *Pocillopora madreporacea* from Ihéu de Baixo off Porto Santo in the Madeira Islands (see Baarli et al., 2014 for details).

Figure options

Fig. 20.

Miocene rhodolith limestone from Ihéu de Cima off Porto Santo in the Madeira Islands.

(see Johnson et al., 2011 for details).

Figure options

4.2. *Tuamuto* Archipelago (South Pacific Ocean)

During the United States Wilkes expedition sometime after August 14, 1838, the *Peacock* sailed along the shores of Dean's Island, the largest in the Tuamuto Archipelago, now called Rangiroa. No landings were attempted, but Dana (1853 p. 127) recorded: “We observed that the rim of land consisted for miles of an even wall of coral rock, apparently six or eight feet above high tide” (Fig. 21). He also noted that the limestone formation was “broken into rude columns” and in places showed evidence of uplifted arches and former sea caves. Dana estimated the amount of island uplift to be about six feet (nearly 2 m). The smaller, nearby Metia Island (today's Makatea) was measured by Dana to have been elevated 250 ft (76 m), which conforms to modern topographic maps for the rim of this uplifted atoll with its interior pits excavated for phosphate deposits as late as 1964. Thus, Dana became the first geologist to credit substantial evidence for island uplift in the Pacific Ocean basin based on his visit. Subsequent work by Montaggioni et al. (1985) on Makatea verified Dana's basic observations. More typically, however, the many islands in the Tuamuto Group represent one of the greatest concentrations of atolls that constitute the subsidence of former volcanic islands found anywhere in the Pacific Ocean.

Fig. 21.

Uplifted limestone shores from Rangiroa Island in the Tuamuto archipelago. Photo credit: A. Bruckner (Khaled bin Sulgtan Living Oceans Foundation).

Figure options

4.3. Tahiti in the Society Islands (South Pacific Ocean)

Tahiti is the only place visited both by Darwin and Dana that influenced their separate studies. The *Beagle* anchored in Matavai Bay off the northwest coast of Tahiti on November 15, 1835 and departed from Pape'ete on November 26. Two key activities occupied Darwin during his stay. The first entailed inland exploration in search of evidence for uplift. On November 17, he made a solo climb above Matavai Bay to an elevation of about 900 m, where he enjoyed a clear view across to neighboring Eimeo Island (today's Mo'orea) separated from Tahiti by 16 km. From that vantage, Darwin (1839, p. 484) observed that “a narrow but well-defined brilliantly white line was visible, where the waves first encountered the wall of coral” representing the barrier reef around the island. A closer, contemporary view of the barrier reef that encircles Mo'orea is shown in Fig. 22. The following day, Darwin enlisted guides to lead him on a 14-km trek through Tia Arue Valley, which involved a climb on steep slopes to camp at a much higher elevation at the head of the valley. No traces of fossil coral were found, although Darwin (1844) cites contemporary sources to suggest otherwise elsewhere on the island. Dana (1853) considered such sources to be questionable and the modern literature offers no trace of reports about uplifted coral rock on Tahiti. On the contrary, Thomas et al. (2009) studied submerged reefs off Tahiti ranging in depth from 42 to 117 m that were cored and dated to the last interglacial epoch 137,000 years ago when sea level formerly was higher than today. The study by Ménabréaz et al. (2010) also describes subsidence in an Upper Pleistocene reef sequence based on cores taken off the south coast of Tahiti at Maraa. Island subsidence continued to occur during Holocene time, based on Younger Dryas corals sampled and dated from boreholes drilled onshore of the Pape'ete barrier reef in Tahiti (Bard et al., 2010).

Fig. 22.

Barrier reef around Mo'erea, Tahiti in the Society Islands. Photo credit: Josh Krantzer.

Figure options

Darwin's other activity was to experience a living coral reef. On November 22, he hired a canoe and paddlers to bring him out to the edge of the barrier reef skirting Tahiti. Writing in his *Beagle* diary for that day (p. 378), Darwin recorded that “We paddled for some time about the reef admiring the pretty branching corals.” It was his first look at a genuine coral reef, and he was moved to reflect on how “little is yet known…. of the structure and origin of the coral islands & reefs.”

The *Peacock* reached the same Matavai anchorage used by the *Beagle* nearly three years later on September 12, 1838. One of the expedition's artists, A.T. Agate, rendered a sketch of nearby Mo'orea from inside the surrounding barrier reef and lagoon that features the island's rugged core. Dana was impressed by the power of erosion effected by streams and rivers on Tahiti and Mo'orea, and he reasoned that the subsidence of such deeply eroded islands would result in an irregular coastline with indented bays. February 21, 1840 the *Peacock* reached Australia's Sydney Harbor and Dana soon learned about Darwin's nascent ideas on atoll development from a newspaper story.

4.4. Tonga Islands

From Sydney, the *Peacock* reached Tongatabu on April 30, 1840 and remained in the island group until May 5. The only island in the Tonga Group where Dana went ashore was Tongatabu, which he characterized as an elevated atoll. From shipboard 10 miles (17 km) southeast of Tongatabu, Dana described the neighboring island of Eua as featuring a rocky shoreline (Fig. 23) formed by uplifted coral-reef rock with a thickness of 20 ft (6 m). He added that it was possible to see three levels of elevated terraces eroded in limestone and that the island core consisted of basalt. Quoting local sources, Dana suggested that corals could be found 300 ft (>90 m) above sea level. According to research by Tappin and Balance (1994), the succession of Pliocene and Pleistocene terraces rises to an elevation of 550 ft (168 m) above sea level. Some of the limestone Dana viewed from a distance probably was formed by rhodoliths, because rhodolith fossils that span the Middle to Upper Eocene are reported from Eua as part of a thick, shallowing-upwards sequence exposed at several localities close to the beach along the length of the island (Buchbinder and Halley, 1985; Tappin and Balance, 1994). The rhodoliths at the bottom of the sequence consist of coralline red algae encrusted around volcanic pebbles. Thick layers of rhodoliths lacking basalt cores follow above. Islands in the Tonga Group are classified as part of the Tonga-Kermadec Arc with a complicated tectonic history involving several phases of subsidence and elevation associated with ocean-plate to ocean-plate subduction (Tappin et al., 1996). Each phase of subsidence resulted in deposition of strata with mixed carbonate and volcanic sediments.

Fig. 23.

Uplifted Pliocene-Pleistocene limestone on the south shores of Eua in the Tonga Islands. Photo credit: Karsten Rau.

Figure options

4.5. Fiji (South Pacific Ocean)

From May 6 to August 11, 1840, the *Peacock* and the *Vincennes* were committed to survey work in the Fiji Islands where detailed charts were drawn providing examples for all three stages in the progression of island development leading to atolls. With a diameter of 7 km, Chichia (Cicia) in the east-central sector is typical of an island with a fringing coral reef. In the group's south-central sector, Matuka is roughly the same size but features a barrier reef separated from the shore by a lagoon up to 1.5 km wide. Nearby the main island of Fiji, Nanuku is fairly representative of an atoll but with a small island displaced off to one side within a large, oval-shaped atoll having a maximum diameter of 28 km.

Dana (1853 p. 131) equivocated on the overall extent of uplift throughout this island group, citing data for minor uplift on some of the larger islands but suggesting subsidence for some of the smaller islands based on barrier reefs in the group's eastern sector. In contrast, detailed studies by Ladd and Hoffmeister (1945) and Nunn (1996) in the Lau Islands of eastern Fiji, show a succession of uplifted middle Miocene strata, lava flows, and upper Miocene to Pliocene strata (all in the Tokalau Limestone Group) capped by lava flows. Coastal exposures feature eroded terraces with tidal notches and sea caves of Pleistocene age. The stratigraphic succession in the Lau Islands is a result of compressive tectonics associated with the Lau-Colville Ridge (Nunn, 1996). Overall, the setting of the Fiji Islands is clustered around a triple junction that contributes to variable and highly complex tectonics (Nunn and Omura, 1999).

4.6. Hawaiian Islands (North Pacific Ocean)

The *Peacock* was stationed in the Hawaiian Islands from September 24 to December 3, 1840. Dana had at his disposal five days on the big island of Hawaii, where he skirted the shield volcano of Mauna Loa and reached Kilauea on the way to Hilo. The great shield volcanoes (Fig. 24) provide the archetype example for the structure and eruptive behavior represented by this class of oceanic volcano. Dana also recognized subsidiary styles of eruption that resulted in cinder cones and tuff cones arrayed along fissure zones, now called rift arms.

Fig. 24.

View of the shield volcano Mauna Loa on the big island of Hawaii.

Figure options

On Oahu, Dana (1849 p. 252, 1890 p. 302) explored raised coral reef formations all around the island's coast. The most extensive reef limestone is exposed along the southern and southwestern shores, where he observed the thickness of reef rock to vary from 15 to 30 ft (4.5 to 9 m) and estimated that the maximum coastal uplift was on the order of 30 ft. Large-scale laminated structures produced by corals are notable along the shore near Pupukea on the leeward western side of the island. Extensive reef limestone occurs along the northeast coast at Kahuku Point, at Laie Beach, and at Waimanalo Beach to the southeast. Dana (1849 p. 253–255) also described coral sand rock that represents former beaches and dunes emplaced on the windward side of the island. Dune rocks that exhibit large-scale laminations and cross beds are especially well exposed in coastal outcrops at Laie Point. To our knowledge, no petrographic studies have been conducted to test the possible contribution of rhodolith-derived carbonate sand in these dune rocks. Dana and many later researchers were not attuned to the possible occurrence of fossil rhodoliths as a component of Pleistocene limestone on Oahu. Good examples of whole rhodoliths and coarse rhodolith debris are present in Holocene beach rock on the northwest coast of Oahu along the outer-exposed arm of the headland west of Kawela Bay (Fig. 25 ; Fig. 26). Miocene reef deposits offshore Oahu (Menard et al., 1962) indicate an early history of subsidence was likely to have occurred when the island sat over the lithospheric hot spot much like the big island of Hawaii today. More recent research has re-focused on the Pleistocene history of Oahu with an emphasis on unusually high rates of uplift based on improved dating of corals (Muhs and Szabo, 1994; Grigg and Jones, 1997; Muhs et al., 2002; McMurtry et al., 2010; Huppert et al. 2015). Uplift is associated with flexure of the ocean crust after the island (and others farther afield) shifted westward from the lithospheric hot spot.

Fig. 25.

View of Holocene beach rock dipping into the ocean off the northwest (leeward) side of Oahu in the Hawaiian Islands.

Figure options

Fig. 26.

Close-up view from the Holocene beach rock shown in Fig. 26, showing whole rhodoliths and associated rhodolith debris (coin for scale is 2 cm in diameter).

Figure options

The following year in 1841, the *Peacock* sailed among islands belonging to the Samoan, Gilbert, and Marshall archipelagos from February 5 to May 9, which permitted Dana to consider island chains with orientations similar to the Hawaiian chain. The *Peacock* returned to Honolulu harbor for repairs June 14–21, which gave more time for investigations on Oahu. Sometime during these two visits to the Hawaiian Islands, Dana spent four days on Kauai, where he took the measure of the island's physical geography and state of erosion. The contrast in comparison with other islands in the Hawaiian chain allowed him to argue not that Kauai was appreciably older, but that volcanism had long since become quiescent compared to the others.

4.7. Cocos (Keeling) Islands (Indian Ocean)

The *Beagle* put in to Port Refuge on April 1, 1836 and subsequently devoted 10 days to exploration of the island shores forming the south atoll with a lagoon 9.5 miles (15 km) in maximum diameter (Fig. 27). On leaving the southern atoll on April 12, Darwin (1842 p. 8) described a profile on the margin of an islet at the head of the lagoon, where: “At a distance of 2,200 yards from the breakers, Captain FitzRoy found no bottom with a line 7,200 feet in length; hence the submarine slope of this coral formation is steeper than that of any volcanic cone.” Earlier from the reef flat, Darwin (1842, p. 6) reports that: “It is possible only under the most favourable circumstances, afforded by an unusually low tide and smooth water, to reach the outer margin, where the coral is alive.” *Porites* in “irregularly rounded masses from four to eight feet broad” dominated the reef edge where the waves broke with great force, although the day was otherwise calm. The stinging coral, *Millepora*, was found to be common but secondary in abundance to the *Porites*. Most likely measured out on West Island (Fig. 28), a profile through approximately a half-kilometer wide portion of the South Keeling atoll shows changes in composition and elevation from one side to the other (Darwin, 1842, p. 6).

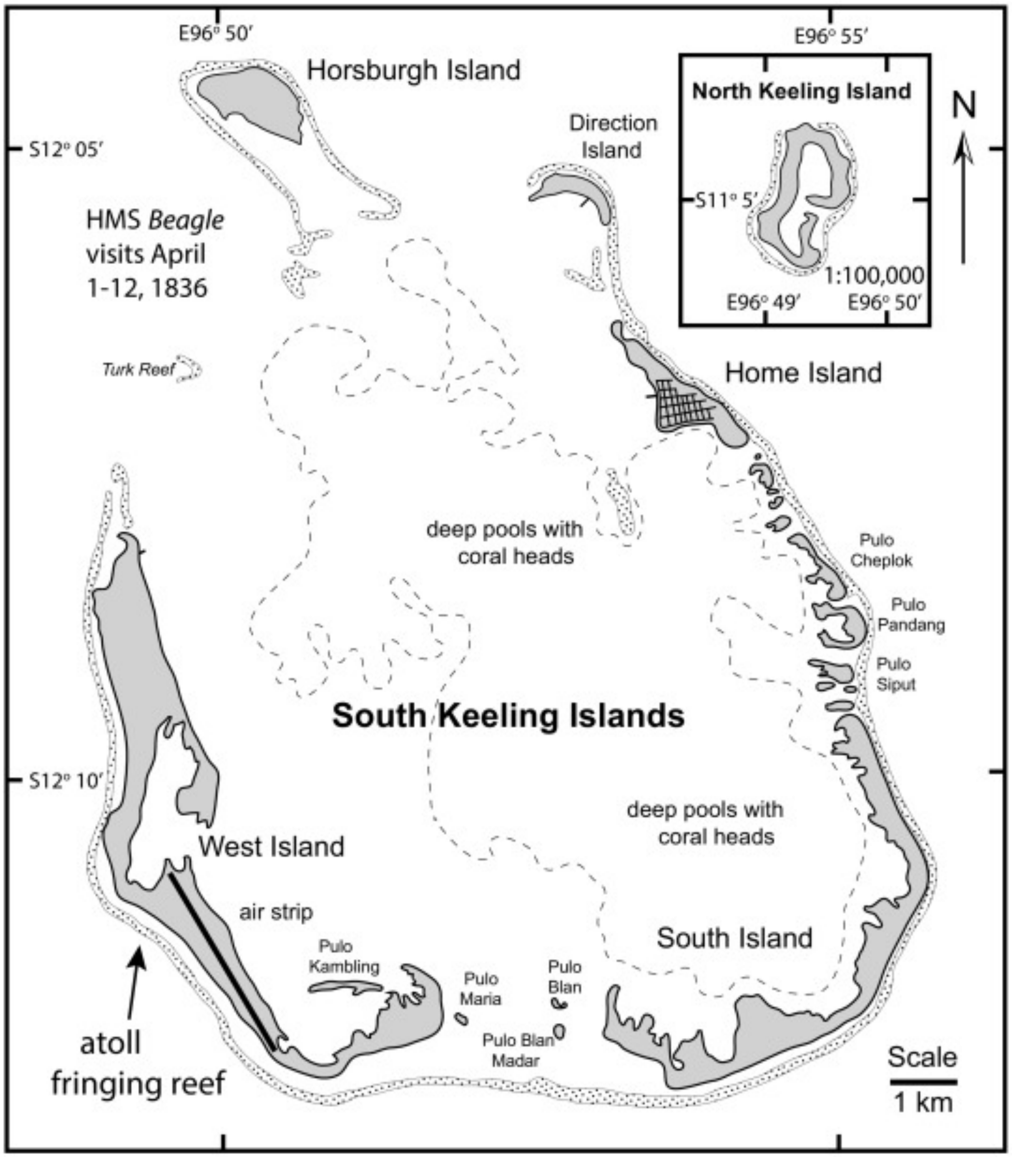

Fig. 27.

Map of the Cocos (Keeling) Islands in the Indian Ocean (after an original source in the Perry Castañeda Library, University of Texas, Austin, Texas).

Figure options

Fig. 28.

Crystal Rock (uplifted limestone) in Tamarin Bay with Le Morne Mountain on Mauritius Island in the background. Photo credit: Photobucket.

Figure options

It is notable that Darwin (1842 pp. 9–10) applied the term “nulliporae” to growths represented by the “lowest classes of the vegetable kingdom” (i.e. coralline red algae) that armor plate the outer reef edge where the waves break for the longest interval during each tidal cycle. There on the main Cocos atoll, he saw different manifestations of living coralline algae that included: 1) thin sheets, 2) strong knobs (as thick as a man's finger), and 3) branches with knobbed extremities. No nulliporae were found from the lagoon margin on the opposite, sheltered side of the reef flat. The description is relevant, particularly in light of recent discoveries regarding coralline red algae that fill a similar growth pattern, but thrive in places entirely without corals, as around Ascension Island (Fig. 15). Dana never visited the Cocos Islands, but confirmed Darwin's observations about encrusting coralline red algae on the outer margins of reef platforms widespread throughout the Pacific Ocean. Moreover, he observed (Dana, 1849 p. 36): “Other nodular and branching Nullipores grow in the more sheltered cavities, where they are not easily dislodged by the waves.”

One of the few recent studies to revisit the Cocos Islands examined coral-rich limestone buried from 8 to 11 m below the modern reef flats in the Cocos Islands and found a correlation with the last interglacial high stand in sea level attributed to oxygen isotope substage 5e (Woodroffe et al., 1991). This result provides evidence for atoll subsidence, because sea level 125,000 years ago was significantly higher than present sea level by as much as 5–7 m based on widespread geographic correlation of oxygen-isotope excursions that serve as a proxy for sea-level change as reviewed by Railsback et al. (2015).

4.8. Mauritius Island (Indian Ocean)

From April 29 until May 9, 1836, the *Beagle* sheltered at Port Louis on the western shore of Mauritius. Darwin (1842 p. 51) commented on the fringing reef that surrounds the island except for places where the coast plunges too precipitously for coral attachment or where there is outflow of streams or rivers. He cited original data based on soundings to show that the water depth beyond the reef edge drops off much more gradually than found seaward of the great atoll in the Cocos Islands. With regard to island uplift, Darwin (1844 pp. 28–29) described limestone hillocks on the coastal plain southeast of Port Louis that reach a thickness of 20 ft (6 m) with mixed fragments of basalt and "great blocks" of coral. He also took note of basalt flows covered by a "conglomerate of corals and shells" for a considerable distance inland along the coastal plain north of Port Louis. Crystal Rock (Fig. 28) represents another feature showing uplifted limestone in Tamarin Bay, a feature not mentioned by Darwin but one popular with tourists to Mauritius today. According to Montaggioni (1982), large continuous outcrops of Pleistocene reef limestone are scarce on the island and the best surviving exposure is located within Port Louis harbor, where it extends for a distance of 50 m at an elevation 6 m above mean sea level. It is odd that Darwin did not mention this outcrop; perhaps it was not visible at the time of his visit.

5. *Trans*-oceanic migrations on island steppingstones

The pioneering studies by Darwin and Dana as explorers of oceanic islands were by no means limited to geology. Certain barnacles collected during the voyage later became the centerpiece of Darwin's extensive taxonomic work on that group. The thin sections for microscope study made by Darwin during detailed work between 1846 and 1854 are still to be found in the Zoology Museum at Cambridge University (Stott, 2003). It was halfway through the United States Exploring Expedition in 1840 on reaching the Fiji Islands that Dana assumed responsibilities for the collection and taxonomic study of corals. The Smithsonian collections at the US National Museum of Natural History register 313 coral specimens comprising 240 species from Dana's work (Viola and Margolis, 1985). Attached mainly to hard substrates during their adult lives, barnacles and corals are conservative organisms with regard to geographic dispersal. Generally, expansion of the biogeographic range for such species is limited to the circulation of sexual gametes and free-swimming larval forms, which in individual organisms rapidly conclude with metamorphosis into a settled state. Within the context of any particular climatic zone, migration along a continuous continental coastline is accomplished through gradual dispersal by successive generations during pelagic stages of development. Wide oceans and unfavorable surface currents account for significant blockages to the trans-oceanic migration of barnacles and corals, but such circumstances may be mitigated by island steppingstones that serve as strategic way stations across an otherwise formidable barrier.

5.1. Biogeography of the Coral-dwelling Barnacle Ceratoconcha

During his initial visit to Santiago in the Cape Verde Islands in 1831, Darwin collected a small solitary coral, *Coenopsammia.* Several pyrgomatid barnacles (probably *Adna anglica*, the only reported extant pyrgomatid from the Cape Verdes) were imbedded along the rim of the coral. In his zoology notebook (Darwin, 2005 p. 12–13), he described the barnacles at length under the genus name *Pyrgoma.* He had managed to extract one of the animals from its cavity in the coral and observed eggs belonging to the species. At the conclusion of his journal entry on this topic, the young naturalist noted correctly that no one before him had described the living *Pyrgoma* animal. Darwin already knew about barnacles, because he had learned to dissect marine invertebrates as a pre-medical student at Edinburgh University under the Scottish doctor, Robert

Grant. All through the ensuing voyage of the *Beagle*, Darwin would apply this knowledge and he continued to collect a large number of barnacle specimens among many other invertebrates. The passion he developed for barnacles resulted ultimately in his seminal four-volume treatise published by the Ray Society between 1851 and 1855.

In living marine communities, barnacles belonging to the family Pyrgomatidae are among the most common and well known obligatory associates hosted by scleractinian corals and also some alcyonarians, hydrozoans and sponges (Hiro, 1935; Moyse, 1971; Ogawa and Matsuzaki, 1992; Ross and Newman, 2002). They are found on >200 different species of corals (Ross and Newman, 2002). Darwin (1854) identified all coral-inhabiting barnacles as *Pyrgoma*. Today the group is split into three subfamilies based on how many opercular and wall-plates they possess. The genus *Ceratoconcha* (Ceratoconchinae) has unmodified opercular valves and a four-plated wall. It lives exclusively on hermatypic corals and has with one exception in the Miocene/Pliocene transition of southeast California (Redman et al., 2007) been restricted to the Atlantic Ocean. The first examples of the pyrogomatic barnacle *Ceratoconcha* from Miocene strata on Ilhéu de Cima off Porto Santo (Madeira) were described by Santos et al. (2012), which stimulated a resurgence of research on this genus. *Ceratoconcha* also happen to provide a good example of an organism that used oceanic islands as stepping-stones during dispersal and as refuges during the major decline of their host organisms (Baarli et al., 2017).

Confirmed records of *Ceratoconcha* appeared nearly simultaneously during the early Miocene (earliest Burdigalian Age) in lower Miocene strata of Florida (Chipola Formation: Ross and Newman, 2002) and in the French Aquitaine Basin on the eastern side of the Atlantic (Baarli et al., 2017). Other barnacles and also mollusks suggest close affinities between the two sides of the Atlantic during a warmer time when coral reefs occurred farther north than now (Perrin and Bosellini, 2012). This also was at time of weaker gyre circulation (Vermeij, 2012) that led to the build-up of warm water near the equator, a condition favorable for strong hurricane activity (Johnson et al., 2011). The circulation pattern affecting larvae dispersal was in two directions with the North Equatorial current set up by the trade winds from east to west as opposed to a hurricane-driven pattern from west to east. Dispersal was abetted by several early Miocene oceanic islands vulnerable to tectonic subsidence that acted as stepping stones. On the way from east to west, barnacle larvae may have taken advantage of the Madeira Tore Rise, the Canary Island Seamount Province and the Cape Verde Rise, each with exposed islands at that time. Farther west in the Atlantic Ocean, the Verma and Romanche islands (now submerged) were in place (Corda and Palmiotto, 2015). Bermuda was a much larger island during the early Miocene than today (Vogt and Jung, 2007) and it lay in the middle of the hurricane track from west to east. Furthermore, potential coral-reef hosts existed as far north as Germany (Perrin and Bosellini, 2012) shortening the distance of barnacle larvae migration.

Globally, hermatypic corals suffered a major decline during the transition between Miocene and Pliocene times and they nearly disappeared in the Mediterranean along the coast of Western Europe (Vertino et al., 2014). However, in the Cape Verde Islands corals occur in upper Miocene through Pliocene strata (Johnson et al., 2014). Coral populations also existed during the Pleistocene and Holocene to the present, as for example on Sal Island (Zazo *et al*., 2007 ; Zazo *et al*., 2010). *Ceratoconcha* of Pleistocene age at Maio in the Cape Verde Islands represents the first fossil pygomatid barnacle recorded from these islands and the last to survive in the eastern part of the Atlantic (Baarli et al., 2017). Thus, these islands served as a refuge both for *Ceratoconcha* and their host corals.

5.2. Biogeography of reef-forming corals

Dana (1846) compiled an enormous amount of information on the “zoophytes” or hard and soft corals, issued as Volume 7 of the United States Exploring Expedition. In the preface to this work, he records that 261 species of corals were collected during the expedition, among which 203 are said to be new to science. Reef-forming corals were defined as consisting of species in seven families, including the Astraeida, Fungidae, Caryophyllidae, Gemminporidae, Madreporidae, Favositidae, and Poritidae. Dana (1846, p. 104) broke new ground with his tabulation on the relative diversity of species among these families compared between the Caribbean Sea (West Indies), the Indian Ocean and Red Sea (East Indies), and the Pacific Ocean. Based on the expedition's collections, he found that the number of reef-forming corals was nearly twice as high in the Indian Ocean as in the Caribbean (117 vs. 60 species) and highest of all in the Pacific Ocean (162 species). This approach prefigured later research on generic diversity gradients and centers of dispersal for a wide variety of plants and animals, including modern hermatypic corals (Stehli, 1968; Veron, 1995). In particular, Stehli (1968, his Fig. 45) was the first to map global gradients showing that the highest concentration of reef-forming coral genera occurs in the western Pacific Ocean in the waters of Indonesia and New Guinea.

With regard to major physical factors limiting the geographic range of reef-forming corals, Dana (1846 p. 102) was adamant about the importance of variations in surface-water temperature which he pegged to a mean annual water temperature of 68° F (or 20 °C). He acknowledged that corals might survive in cooler waters down to 66° F or even 64° F, but that the ability for reproduction was negatively impacted. Dana (1846 p. 102) further observed that the “warmest parts of the Pacific vary from 80° F to 85° F (or 29° C), where the Astreaeas, Meandrinas, Maddrepores, etc., are developed with peculiar luxuriance.” Here Dana begins to expound on regional differences regarding reef-forming corals. He made special note of the fact that the Hawaiian Islands are located near the northern limits of the coral seas, where the “Porites and Pocilloporae prevail, and there are very few species of the general Astraea, Mussa, and Meandrina, which are common nearer the equator” (Dana, 1846 p. 102).

Dana (1872) took the opportunity to expand his studies on corals and refine his concept of temperature controls on geographic range, providing the first modern chart showing the limiting boundaries of the 68° F (20° C) isotherm in ocean waters around the world. He considered that coral biogeography was divided into two major regions, distinguished as the torrid and subtorrid zones. The Fiji Islands are cited as the epitome of coral diversity, where the “temperature of the surface is never below 74° F for any month of the year and all the prominent genera of reef-forming species are abundantly represented (Dana, 1872 p. 110). In contrast, he wrote that “The Hawaiian Islands, in the north Pacific, between the latitudes 19° and 22° are outside the torrid zone of oceanic temperature, in the subtorrid, and the corals are consequently less luxuriant and much fewer in species” (Dana, 1872 p. 111). In particular, Dana observed that Hawaiian waters support a profusion of “hardier” species in the dominant genera *Porities* and *Pocillipora*. In lower-diversity settings, certain coral species tend to dominate the ecospace and this is very much the case in Hawaii where *Pocillopora meandrina* occupies places with strong wave energy and *Porites lobata* takes over in places that are more protected, whereas *Porites compressa* is restricted to the most sheltered waters (Fielding and Robinson, 1993).

Despite the presence of a laterally extensive climate zone parallel to the equator, Dana clearly understood the possible effect of an east-west filter to species migration writing (1872 p. 111) that "At the eastern [end] of the Pacific coral islands, the Paumotus, which are within the limits of the torrid region, the variety of species and genera is large, but less so than to the western." He elaborated further that generic coral diversity is even more severely restricted from the Gulf of California through to the Gulf of Panama and south to Guayaquil, Ecuador, but in this case on account of cold-water currents. In this guise, Dana explained the apparent lack of coral species in the Galápagos Islands with his argument that the 68° F isotherm excludes those islands from the coral seas "making a bend around them and passing for a short distance even north of the equator" (Dana, 1872 p. 300). García-Talavera (1993) discussed the 1954 uplift of a coral reef at Urbina Bay in a sheltered cove on the west side of Isla Isabel in the Galapagos Islands, which left exposed a fauna of large and long-lived corals. Despite seasonally cold waters brought north by the Humboldt Current, corals affiliated with the Indo-Pacific diversity gradient managed to reach the Galápagos Islands and thrive under local conditions in semi-protected spots.

All present-day corals in the Hawaiian Archipelago originated in the Indo-Western Pacific oceans with the Kuroshio Current and Subtropical Counter-Current serving as the primary pathways along which coral larva drift to Hawaii (Grigg, 1997). The available fossil data show that reef corals first reached the Hawaiian island chain during the Early Oligocene 34 million years ago. Grigg (1997) argues that a combination of factors including the isolation of Antarctica, global cooling, and an increase in latitudinal temperature gradients caused an intensification in gyral surface currents in the north Pacific Ocean. With stronger currents that moved free-swimming coral larvae at a faster speed, it was possible for coral species to reach the outer islands (now represented by the Emperor Seamounts) and migrate from island to island along the chain, whereas prior to that time the region was isolated from the center of highest diversity in the Indo-Western Pacific oceans. A possible corridor for colonization of the Hawaiian chain's middle section of islands and shoals is from the island way-station of the Johnston Atoll, located 865 km to the south-south-west (Kobayashi, 2006). For example, the critical survival period for coral larvae to last while carried by currents between the Johnston Atoll and the French Frigate Shoals in Hawaiian waters is between 40 and 50 days. Not all coral species have this staying power. According to Grigg (1997), the number of extant reef-coral species in Hawaii is still <10% the number of species found in the center of dispersal located in the West Pacific Ocean. Even so, those particular corals managed to reach and successfully colonize the Hawaiian archipelago.

6. Discussion

6.1. Global patterns and tectonics

Darwin (1844 p. 126) summarized his observations on the distribution of volcanic islands noting the arrangement of archipelagoes "either in single, double, or triple rows, in lines which are frequently curved in a slight degree" and where "each separate island is either rounded or more generally elongated in the same direction with the group in which it stands." He specifically sorted out different lines of orientation as perceived in the Galapagos, Canary, and Cape Verde islands, while admitting those in the Cape Verde group are the "least symmetrical of any oceanic, volcanic archipelago" (see Fig. 29). Had Darwin known the orientation of Fernando de Noronha in relationship to the nearby seamount at Alto Fundo Drina and more distal Atol das Rocas in the South Atlantic, he probably would have classified those features as conforming to a single line.

Fig. 29.

Map showing the distribution of Macaronesian archipelagos in the North Atlantic Ocean, many of which feature fossil rhodolith deposits.

Figure options

Dana (1849 p. 157) understood how volcanoes in "two parallel series" are aligned in the Hawaiian Islands. He realized that the chain extended farther northwest beyond Kauai to other islets and atolls. Expressed as quasi-parallel lines connecting the twin loci of shield volcanos in the Hawaiian Islands, these relationships were subsequently mapped by Jackson et al. (1970), their (Fig. 1). However, Dana mistakenly argued that the big island of Hawaii was not the most recent in the group, but was formed by volcanoes "only the last of the number to become extinct" (Dana, 1849 p. 157). He believed that the islands formed simultaneously, fed by magma from the same pair of fractures that became progressively closed in one direction from west to east. The same reasoning was applied to other linear chains of volcanic islands typical of the Pacific Ocean that show a similar orientation to the Hawaiian chain. At the same time, Dana clearly applied criteria based on the physical erosion and subsidence of islands starting from pristine volcanic shields and ending with the morphology of an atoll. According to Dana, this assessment accounted for the amount of time elapsed since volcanic quiescence from one island to the next.

Darwin's exposure to volcanic islands in the North Atlantic and the eastern Pacific (Galápagos Islands) was radically different from Dana's experience with more orderly island chains in the central and western Pacific. The physical evolution of oceanic islands in different places follows different rulebooks as related to plate tectonics. Fast-moving plates like the Pacific Plate with a speed of about 10 cm/yr (Table 1) feature hotspots linked to short-lived volcanoes that move away from the hotspot rapidly and succumb to ongoing erosion and subsidence in a linear progression, whereas slow moving or stationary plates with a speed of 2 cm/yr are not only penetrated by hotspots but also buoyed by injection of magma beneath long-lived edifices that cluster together and experience little or no subsidence or even episodic uplift (Ramalho et al., 2013). Darwin's disorderly Cape Verde archipelago is a prime example of an island cluster attributed to a stationary hotspot relative to the melting source, resulting in episodic growth over a lithospheric swell (Ramalho et al., 2010). The Madeira archipelago also is located on a slow-moving plate with respect to its melting source. The main island of Madeira exhibits evidence for pronounced uplift during the early stages of island building amounting to 400–750 m. The remains of a Miocene tropical to sub-tropical shoreline, representing onlap and development of a small fringing coral reef on a steep rocky shore, are exposed at an elevation between 320 and 430 m above present sea level in the valley of São Vicente (Ramalho et al., 2015).

Irrespective of patterns in surrounding islands, individual islands may express unique growth trends. For example, Santa Maria Island is the oldest in the Azores, having first emerged as a result of Surtseyan activity about six million years ago. It is a typical North Atlantic volcanic island in the sense that its superstructure was never sheltered by a protective coral reef. After initial emergence, island subsidence lasted until 3.5 million years ago followed by 200 m of uplift that has continued until today as shown by a series of well-developed marine terraces on the western side of the island (Ramalho et al., 2017). Such a long-term trend in uplift is modeled on a changeover from dominantly extrusive shield-building activity to dominantly intrusive growth associated with crustal thickening.

In hindsight, it is a historical peculiarity that the geological reputation of Darwin (1842) rests largely with his formulation of the model for atoll development as a result of volcanic island subsidence in concert with more-or-less continuous growth by coral reefs. It was a position subscribed to early on by Dana (1843), stimulated by advance knowledge of the Darwin hypothesis. Alexander Agassiz was one of the most ardent opponents of the subsidence model, devoting 30 years of his life to extensive travel and field research throughout the Pacific and Indian Oceans (Dobbs, 2005). On the other side of the debate was the Australian geologist, T.W. Edgeworth David, who from 1896 to 1898 supervised expeditions to Fanafuti in the Ellise Islands for the express purpose of verifying the Darwin hypothesis. In the final year of David's operation, the drilling crew cored 127 m of coral limestone without reaching basement rock (Branagan, 2005). Although basalt was not attained, the David expeditions were regarded as a partial success due to the consistent shallow-water development of coral limestone through a substantial depth of core.

The ultimate verification of the Darwin hypothesis came only in 1950 with the results of a deep-drilling program on Eniwetok Atoll in the western Marshall Islands under the supervision of the U.S. Navy in preparation for testing of nuclear explosions. After drilling through 1280 m, the drills hit basalt basement (Dobbs, 2005). Microfossils from the base of the overlying limestone formation indicted that reef growth commenced >30 million years ago during the Eocene and continued at a rate of 2.5 cm per 1000 years.

Darwin's model is thus accepted as a valid framework for reef evolution and his classification of reef morphologies have stood the test of time. At a finer scale, however, subsidence does not fully explain the diversity of modern and preserved reef morphologies present in the oceans. Other factors need to be considered in order to fully explain their differences (Scott and Rotondo, 1983; Toomey et al., 2013; Ramalho et al., 2013). In this regard, the key contribution by Reginald A. Daly, 1915 must be considered, who in 1915 in his seminal work on “The Glacial-Control Theory of Coral Reefs” keenly observed that coral reef morphology must also reflect the effects of Pleistocene glacio-eustatic changes The modern perspective is that the diversity in the morphology of modern reefs results from the combined effects of subsidence (or sometimes uplift), coral accretion rates, and Pleistocene glacio-eustatic cycles (Woodroffe et al., 1999; Toomey et al., 2013; Ramalho et al., 2013). It is now appreciated that coral reef profiles and the formation of barrier reefs are mainly controlled by subsidence and vertical rates of coral accretion, as Darwin suggested, but the morphology of modern reefs forcibly bears the strong imprint of Pleistocene glacio-eustatic cycles, as Daly proposed (Toomey et al., 2013; Ramalho et al., 2013).

Darwin's observations on both subsidence and uplift patterns can now be analyzed under the light of modern theories, which relate island isostasy with the geodynamic framework provided by plate tectonics, plate flexure in response to volcanic loading, and the intrusive processes operating on the volcanic edifices themselves (e.g. McNutt and Menard, 1978; Scott and Rotondo, 1983; Stein and Stein, 1992; Grigg and Jones, 1997; Ramalho et al., 2010; Huppert et al., 2015; Ramalho et al., 2017). Ironically, whereas island subsidence is generally well understood under the framework of plate tectonics and flexural loading, island uplift is more of a challenge to explain (Ramalho et al., 2017). Darwin's pioneering observations on island uplift, therefore, set the stage for future research in what is perhaps one of the last major challenges to resolve in our path to fully comprehend worldwide ocean island evolution.

6.2. Island limestone facies

Coral reefs, both past and present, have a spotty record in the North Atlantic region that extends from the Azores to the Cape Verde Islands. Dana (1843) took note of fossil corals in the Madeira Islands, but otherwise his vast experience with reef-forming corals was acquired in the Pacific Ocean. Pleistocene corals do occur in the northeastern part of the Atlantic, as at Ponta das Bicudas on Santiago and Sal in the Cape Verde archipelago (Zazo et al., 2007; Baarli et al., 2013), as well as some Canary Islands (Muhs et al., 2014). Except for Miocene Madeira, these occurrences do not constitute integrated reef structures. Darwin was cognizant of the general scarcity of living corals in the Atlantic Ocean and posed the question whether or not sediment from rivers flowing into Africa's Gulf of Guinea impeded coral growth. In answer to his own query, he wrote (Darwin, 1842 p. 62): “But the islands of St. Helena, Ascension, the Cape Verde, St. Paul's, and Fernando Noronha are, also, entirely without reefs, although they lie far out at sea, are composed of the same ancient volcanic rocks, and have the same general form, with those islands in the Pacific, the shores of which are surrounded by gigantic walls of coral-rock." Spalding et al. (2001) suggested that two possible mechanisms are responsible for creating conditions that restrict significant coral reef growth in all of West Africa to shallow protected bays: 1) the existence of a warm, low salinity seasonal current from the Gulf of Guinea, caused by high riverine discharge, which extends its influence along all the coast from Angola to Mauritania; and 2) upwelling offshore Western Africa, resulting in cooler waters.

Darwin's analysis of Pleistocene limestone that skirts the south and eastern shores of Santiago in the Cape Verde Islands (Darwin, 1844) was novel for several reasons that include: 1) correlation of a distinct paleoshore based on unconformable relationships between limestone and underlying basalt formations, 2) identification of "nulliporae" (specifically the unattached, spherical coralline red algae macroids nowadays called rhodoliths) as a major contributor to limestone, and 3) discrimination between basalt flows with subaerial and submarine characteristics in direct contact with limestone to support interpretations of changing water depth and uplift. Among these, Darwin's identification of fossil rhodoliths as a significant component of limestone was the first connection made with living rhodoliths. The insights Darwin achieved on Santiago Island owe much to the fact that he was able to revise and expand his results due to the opportunity for a second visit to the island near the end of his voyage on the *Beagle* (Pearson and Nicholas, 2007).

Visits to other volcanic islands in the Atlantic Ocean were brief and allowed no opportunities for subsequent expansion and re-evaluation, otherwise Darwin would have made valuable connections regarding the pervasive distribution of fossil and modern rhodoliths throughout that region. Limestone deposits often dominated by fossil rhodoliths occur in the Azores, Madeira, Canary, and Cape Verde archipelagos (Fig. 29). The widespread development of offshore rhodolith banks is verified by walking the beaches and carbonate dunes on many islands where rhodoliths are re-deposited in a range of sediments (Johnson *et al*., 2016 ; Johnson *et al*., 2017b). Recent studies show that living rhodoliths and encrusting coralline red algae are the dominant carbonate contributors around Fernando Noronha (Amado-Filho et al., 2012a), the Atol das Rocas (Gherardi and Bosence, 2001), and even Ascension Island (Kuepper and Teiamis, personal commun. 2014). Moreover, the vast Abrolhos Shelf off Brazil in the South Atlantic Ocean supports the largest and most contiguous rhodolith bank in the world, covering 20,900 km^2 (Amado-Filho et al., 2012b). Although the *Beagle* traversed this shelf on the way to and from Brazil on at least four occasions, there was no urgency to chart its islands or to sound its depths. Thus, perhaps Darwin's question on the absence of coral reefs in large parts of the Atlantic Ocean could be rephrased to ask why rhodoliths are so pervasive as an alternate carbonate facies in this part of the world compared to the Pacific and Indian oceans. Research on this topic is so current that the answer remains yet to be found.

The same line of inquiry is presently much in play regarding large-scale patterns in the biogeography of most other marine invertebrates, some marine vertebrates, and marine macroalgae in relation to oceanic islands. Very little research of this kind has been accomplished in contrast to studies on island biogeography related to the spread and island diversity of land plants and land animals. A substantial contribution in this direction was accomplished by Ávila *et al.*, 2018a ; Ávila *et al.*, 2018b with regard to four marine groups (gastropod mollusks, echinoderms, reef fishes, and macroalgae) from a dozen islands and/or archipelagoes in the North and South Atlantic oceans that range from the Azores in the north to Saint Helena Island in the south. Nothing approaching this scale of analysis has been attempted in the Pacific and Indian oceans.

7. Conclusions

Charles Darwin and James D. Dana represent the first generation to consider the geology of oceanic islands in a rigorous way on a global scale. Their investigations embraced all physical aspects of volcanism including subaerial and submarine products, but equally so the organic make-up of limestone associated with island development. Attempts were made to relate the distribution of volcanic islands to patterns of uplift and subsidence. Dana, whose career remained devoted to geology long after Darwin turned his attention entirely to biology, made the Hawaiian chain the chief exemplar of oceanic islands. For Darwin, it was Santiago Island in the Cape Verdes that provided the impetus for his studies on volcanic islands and drew his most critical attention. No two island groups could be more different from one another.

Based on the concept of plate tectonics, the distribution patterns of oceanic islands are seen to reflect variables in geophysical constraints that regulate the birth and death of volcanic islands as a consequence of movements by lithospheric plates over fixed hotspots. Darwin (1842) had his greatest success as a geologist in formulating the atoll hypothesis to explain island subsidence and upward reef growth. Dana, 1849 ; Dana, 1890 had his greatest success as a geologist in combining Darwin's atoll model with a more sophisticated model of age-based island geomorphology. He understood that the relative age of islands in linear chains is reflected by progressive stages of surface erosion and subsidence, but adhered to the mistaken notion that volcanism began at the same time along any given line of islands. Darwin (1844) struggled to make sense of non-linear island clusters in the Atlantic Ocean, but stressed the utility of limestone marker beds as indicators of island uplift. Fixation on this basic Lyellian concept meant that he was on the constant look out for island limestone deposits during his subsequent travels in the Pacific and Indian oceans. Darwin was the first geologist to appreciate rhodoliths as major limestone builders, but he failed to realize just how pervasive these non-attached coralline red algae are in large parts of the North and South Atlantic oceans.

Darwin's work on the systematic zoology of barnacles and Dana's work on corals were focused mainly on biological samples but also considered paleontological data available in the mid-nineteenth century. With the recovery and study of additional fossil material from oceanic islands, the evidence for patterns of dispersal of marine organisms via island steppingstones is becoming better documented.

The axiom that additional opportunities to revisit a locality result in the recognition of more details contributing to a better understanding of that locality is one fully appreciated by all geologists and paleontologists who participate in active field studies. Darwin and Dana did not have this luxury during their circumnavigations through the world's oceans from 1831 to 1836 and 1838–1842, respectively. Fieldwork typically was constrained by single opportunities to visit for a limited amount of time a given island not necessarily of their choosing within a larger archipelago that they were not at liberty to fully canvass. Travel to remote islands now has become much easier in the century and a half since the pioneering studies of Darwin and Dana, but the same axiom applies. Much remains to be learned.

Uncited references

Johnson et al., 2013

Malay and Michonneau, 2014

McBirney and Williams, 1969

Newman and Ross, 1976

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Fig. 30.

Authors belonging to the Macaronesian Working Group, from left to right: Carlos M. da Silva, Mario Cachão, B. Gudveig Baarli, Markes E. Johnson, Ricardo Ramalho, Ana Santos, and Eduardo Mayoral.

Figure options

Appendix A. Supplementary data

Supplementary material

Help with DOCX files
Options

References

1.
- Amado-Filho et al., 2012a
- G.M. Amado-Filho, G.H. Pereira-Filho, R.G. Bahia, D.P. Abrantes, P.C. Veras, Z. Matheus
- Occurrence and distribution of rhodolith beds on the Fernando de Noronha Archipelago of Brazil
- Aquat. Bot., 101 (2012), pp. 41–45
-

2.

- Amado-Filho et al., 2012b
- G.M. Amado-Filho, R.L. Moura, A.C. Bastos, L.T. Salgado, P.Y. Sumida, A.Z. Guth, R.B. Francini-Filho, G.H. Pereira-Filho, D.P. Abrantes, P.S. Brasileiro, R.C. Bahia, R.N. Leal, L. Kaufman, J.A. Kleypas, M. Farina, F.L. Thompson
- Rhodolith beds are major $CaCO_3$ bio-factories in the tropical South West Atlantic
- PLoS One, 7 (2012), Article e35171
-

3.

- Ávila et al., 2014
- S.P. Ávila, H. Calado, M. Cachão
- "Palaeopark Santa Maria" (Azores). IX Congresso Nacional de Geologia
- , 2° Congresso de Geologia dos Países de Língua Portuguesa, (2014) (Porto, 18-24 Julho, 2014)
-

4.

- Ávila et al., 2015
- S.P. Ávila, R.S. Ramalho, J.M. Habermann, R. Quartau, A. Kroh, B. Berning, M.E. Johnson, M.X. Kirby, V. Zanon, J. Titschack, A. Goss, A.C. Rebelo, C. Melo, P. Madeira, R. Cordeiro, P. Meireles, L. Bagaço, A. Hipólito, A. Uchman, C.M. Silva, M. Cachão, J. Madeira
- Palaeoecology, taphonomy, and preservation of a lower Pliocene shell bed (coquina) from a volcanic oceanic island (Santa Maria Island, Azores, NE Atlantic Ocean)
- Palaeogeog, Palaeoclim, Palaeoecol, 430 (2015), pp. 57–73
-

5.

- Ávila et al., 2018a
- S.P. Ávila, R. Cordeiro, P. Madeira, L. Silva, A. Medeiros, A.C. Rebelo, C. Melo, A.I. Neto, R. Haroun, A. Monteiro, K. Rijsdijk, M.E. Johnson
- Global change impacts on large-scale biogeographic patterns of marine organisms on Atlantic oceanic islands
- Marine Poll. Bull., 126 (2018), pp. 101–112
-

6.

- Ávila et al., 2018b
- S.P. Ávila, R.S. Ramalho, J.M. Habermann, J. Titschack
- The marine fossil record at Santa Maria Island (Azores)
- U. Kueppers, C. Beier (Eds.), Volcanoes of the Azores: Revealing the Geological Secrets of the Central North Atlantic Islands, Springer, Berlin (2018), pp. 155–196
-

7.

- Baarli et al., 2013
- B.G. Baarli, A. Santos, E.J. Mayoral, J. Ledesma-Vázquez, M.E. Johnson, C.M. Da Silva, M. Cachão

- What Darwin did not see: Pleistocene fossil assemblages on a high-energy coast at Ponta das Bicudas, Santiago, Cape Verde Islands
- Geol. Mag., 150 (2013), pp. 183–189
-

8.

- Baarli et al., 2014
- B.G. Baarli, M. Cachão, C.M. Da Silva, M.E. Johnson, E.J. Mayoral, A. Santos
- A Middle Miocene carbonate embankment on an active volcanic slope: Ilhéu de Baixo, Madeira Archipelago, Eastern Atlantic
- Geol. J., 49 (2014), pp. 90–106
-

9.

- Baarli et al., 2017
- B.G. Baarli, M.C.D. Mallay, A. Santos, M.E. Johnson, C.M. Silva, J. Meco, M. Cachão, E. Mayoral
- Miocene to Pleistocene transatlantic dispersal of *Ceratoconcha* coral-dwelling barnacles and North Atlantic island biogeography
- Palaeogeog, Palaeoclimat, Palaeoecol, 468 (2017), pp. 520–528
-

10.

- Baker, 1969
- I. Baker
- Petrology of the volcanic rocks of Saint Helena Island, South Atlantic
- Geol. Soc. Am. Bull., 80 (1969), pp. 1283–1310
-

11.

- Bard et al., 2010
- E. Bard, B. Hamelin, D. DeLanghe-Sabatier
- Deglacial meltwater Pulse 1B and Younger Dryas sea levels revisited with boreholes at Tahiti
- Science, 327 (2010), pp. 1235–1237
-

12.

- Barlow, 1958
- N. Barlow
- The Autobiography of Charles Darwin, 1809–1882, with Original Omissions Restored
- Collins, London (1958)
-

13.

- Branagan, 2005
- D. Branagan
- Funafuti: atoll adventuring
- T.W. Edgeworth David (Ed.), A Life, Geologist, Adventurer, Soldier and ‘Knight in the Old Brown Hat’, National Library of Australia (2005), pp. 85–105
-

14.
- Buchbinder and Halley, 1985
- B. Buchbinder, R.B. Halley
- Occurrence and preservation of Eocene squamariacean and coralline rhodoliths: Eua, Tonga
- D.F. Toomey, M.H. Nitecki (Eds.), Paleoalgology, SpringerVerlag, Berlin (1985), pp. 248–256
-

15.
- Clouard and Bonneville, 2005
- V. Clouard, A. Bonneville
- Ages of seamounts, islands, and plateaus on the Pacific Plate
- in: G.R. Foulger, J.H. Natland, D.C. Presnall, D.L. Anderson (Eds.), Plates, Plumes, and Paradigms, Geol Soc Am Special Paper 388, (2005), pp. 71–79
-

16.
- Corda and Palmiotto, 2015
- L. Corda, C. Palmiotto
- Rhodalgal-foramol facies in equatorial carbonates: insights from Jiocene tectonic islands of the Central Atlantic
- Palaeogeog, Palaeoclim, Palaeoecol, 428 (2015), pp. 21–30
-

17.
- Courtillot et al., 2003
- V. Courtillot, A. Davaille, J. Besse, J. Stock
- Three distinct types of hotspots in the Earth's mantle
- Earth and Planet Sci Letters, 205 (2003), pp. 295–308
-

18.
- Daly, 1915
- R.A. Daly
- The glacial-control theory of coral reefs
- Proceedings of the American Academy of Arts and Sciences, 51 (4) (1915), pp. 157–251
-

19.
- Daly, 1927
- R.A. Daly
- The geology of Saint Helena Island
- Proc Am Acad Arts and Sci, 62 (1927), pp. 31–92
-

20.
- Dana, 1843
- J.D. Dana
- On the areas of subsidence in the Pacific, as indicated by the distribution of coral islands

- Am. J. Sci., 2 (1843), pp. 335–355
-

1.
- Dana, 1846
- J.D. Dana
- Zoophytes
- C. Wilkes (Ed.), United States Exploring Expedition during the years 1838, 1839, 1840, 1841, C. Sherman, Philadelphia (1846) (732 p)
-

2.
- Dana, 1849
- J.D. Dana
- Geology
- C. Wilkes (Ed.), United States Exploring Expedition during the years 1838, 1839, 1840, 184, George P. Putnam, New York (1849)
-

3.
- Dana, 1853
- J.D. Dana
- Coral Reefs and Islands
- G.P. Putnam & Co, New York (1853) (144 p)
-

4.
- Dana, 1872
- J.D. Dana
- Corals and coral islands
- Dodd and Mead Publishers, New York (1872) (398 p)
-

5.
- Dana, 1890
- J.D. Dana
- Characteristics of Volcanoes with Contributions of Facts and Principles from the Hawaiian Islands
- Dodd and Mead, New York (1890) (399 p)
-

6.
- Darwin, 1839
- C. Darwin
- Journal and remarks, 1832–1836
- in: R. FitzRoy (Ed.), Narrative of the Surveying Voyages of his Majesty's Ships Adventure and Beagle between the Years 1826 and 1836, Vol. 3, Henry Colburn, London (1839), pp. 1–615
-

7.
- Darwin, 1842

- C. Darwin
- The Structure and Distribution of Coral Reefs, being the First part of the Geology of the Voyage of the Beagle, under the Command of Capt. FitzRoy, RN during the Years 1832–1836
- Smith Elder & Co., London (1842) (214 p)
-

8.
- Darwin, 1844
- C. Darwin
- Geological Observations on the Volcanic Islands Visited during the Voyage of the H.M.S. Beagle
- Smith, Elder & Co. (1844) (175 p)
-

9.
- Darwin, 1854
- Darwin
- A Monograph on the Sub-Class Cirripedia with Figures of all the Species
- Ray Soc Publ, London (1854) (684 p)
-

10.
- Darwin, 2005
- C. Darwin
- Charles Darwin's Zoology Notes and Specimen Lists from HMS Beagle
- Cambridge University Press (2005), p. 468
-

11.
- Dobbs, 2005
- D. Dobbs
- Reef Madness: Charles Darwin, Alexander Agassiz, and the Meaning of Coral
- Pantheon Books, New York (2005) (306 p)
-

12.
- Dott Jr, 1997
- R.H. Dott Jr.
- James Dwight Dana's old tectonics-global contraction under divine direction
- Am. J. Sci., 297 (1997), pp. 283–311
-

13.
- Fielding and Robinson, 1993
- A. Fielding, E. Robinson
- An underwater Guide to Hawai'i. Univ
- Hawaii Press, Honolulu (1993) (156 p)
-

14.
- García-Talavera, 1993
- F. García-Talavera

- Rsultados Cientificos del Proyecto Galapagos
- , Patrimonio de la Humanidad n°3 - Los Moluscos Marinos Fósiles, Museo de Ciencias Naturales, Aula de Cultura, Cabildo de Tenerife (1993), pp. 6–61
-

15.
- Gherardi and Bosence, 2001
- D.F.M. Gherardi, D.W.J. Bosence
- Composition and community structure of the coralline algal reefs from Atol das Rocas, South Atlantic, Brazil
- Coral Reefs, 19 (2001), pp. 205–219
-

16.
- Grigg, 1997
- R.W. Grigg
- Paleoceanography of coral reefs in the Hawaiian-emperor chain – revisited
- Coral Reefs, 16 (Suppl) (1997), pp. S33–S38
-

17.
- Grigg and Jones, 1997
- R.W. Grigg, A.T. Jones
- Uplift caused by lithospeheric flexure in the Hawaiian archipelago as revieales by elevated coral deposits
- Mar. Geol., 141 (1997), pp. 11–25
-

18.
- Herbert, 2005
- S. Herbert
- Charles Darwin, geologist
- Cornell Univ Press, Ithaca (2005), p. 485
-

19.
- Herbert et al., 2009
- S. Herbert, S. Gibson, D. Norman, D. Geist, G. Estes, T. Grant, A. Miles
- Into the field again: Re-examining Charles Darwin's 1835 geological work on Isla Santiago (James Island) in the Galápagos archipelago
- Earth Sci. History, 28 (2009), pp. 1–31
-

20.
- Hickman and Lipps, 1985
- C.S. Hickman, J.H. Lipps
- Geologic youth of Galápagos Islands confirmed by marine stratigraphy and paleontology
- Science, 227 (1985), pp. 1578–1580
-

1.

- Hiro, 1935
- F. Hiro
- A study of cirripeds associated with corals occurring in Tanabe Bay
- Records of Oceanographic Works Japan, 7 (1935), pp. 1–28
-

2.
- Jackson et al., 1970
- E.D. Jackson, E.A. Silver, G.B. Dalrymple
- Hawaiian-Emperor chain and its relation to Cenozoic circumpacific tectonics
- Geol. Soc. Am. Bull., 83 (1970), pp. 601–618
-

3.
- Johnson and Baarli, 2015
- M.E. Johnson, B.G. Baarli
- Charles Darwin in the Cape Verde and Galápagos archipelagos: the role of serendipity in development of theories on the ups and downs of oceanic islands
- Earth Sci History, 34 (2015), pp. 220–242
-

4.
- Johnson et al., 2010
- M.E. Johnson, P.M. Karabinos, V. Mendia
- Quaternary intertidal deposits intercalated with volcanic rocks on Isla Sombrero Chino in the Galápagos Islands (Ecuador)
- J. Coastal Research, 26 (2010), pp. 762–768
-

5.
- Johnson et al., 2011
- M.E. Johnson, C.M. Da Silva, A. Santos, B.G. Baarli, M. Cachão, E. Mayoral, A.C. Rebelo, J. Ledesma-Vázquez
- Rhodolith transport and immobilization on a volcanically active rocky shore: Middle Miocene at Cabeço das Laranjas on Ilhéu de Cima (Madeira Archipelago, Portugal)
- Palaeogeog Palaeoclim Palaeoecol, 300 (2011), pp. 113–127
-

6.
- Johnson et al., 2012
- M.E. Johnson, B.G. Baarli, M. Cachão, C.M. da Silva, J. Ledesma-Vázquez, E.J. Mayoral, R. Ramalho, A. Santos
- Rhodoliths, uniformitarianism, and Darwin: Pleistocene and Recent carbonate deposits in the Cape Verde and Canary archipelagos
- Palaeogeog, Palaeoclim Palaeoecol, 329-330 (2012), pp. 83–100
-

7.
- Johnson et al., 2013
- M.E. Johnson, B.G. Baarli, C.M. Da Silva, M. Cachão, R.S. Ramalho, J. Ledesma-Vázquez, E.J. Mayoral, A. Santos

- Coastal dunes with high content of rhodolith (coralline red algae) bioclasts: Pleistocene formations on Maio and São Nicolau in the Cape Verde archipelago
- Aeolian Res., 8 (2013), pp. 1–9
-

8.

- Johnson et al., 2014
- M.E. Johnson, R.S. Ramalho, B.G. Baarli, M. Cachão, C.M. Da Silva, E.J. Mayoral, A. Santos
- Miocene-Pliocene rocky shores on São Nicolau (Cape Verde Islands): contrasting windward and leeward biofacies on a volcanically active oceanic island
- Palaeogeog, Palaeoclimatol, Palaeoecol, 395 (2014), pp. 131–143
-

9.

- Johnson et al., 2016
- M.E. Johnson, B.G. Baarli, C.M. Da Silva, M. Cachão, R.S. Ramalho, A. Santos, E.J. Mayoral
- Recent rhodolith deposits stranded on the windward shores of Maio (Cape Verde Islands): historical resource for the local economy
- J Coastal Res., 32 (2016), pp. 735–743
-

10.

- Johnson et al., 2017a
- M.E. Johnson, A. Uchman, P.J.M. Costa, R.S. Ramalho, S.P. Ávila
- Intense hurricane transports sand onshore: examples from the Pliocene Mallbusca section on Santa Maria Island (Azores, Portugal)
- Mar. Geol., 385 (2017), pp. 244–249
-

11.

- Johnson et al., 2017b
- M.E. Johnson, J. Ledesma-Vázquez, R.S. Ramalho, C.M. Da Silva, A.C. Rebelo, A. Santos, B.G. Baarli, E. Mayoral, M. Cachão
- Taphonomic range and sedimentary dynamics of modern and fossil rhodolith beds: Macaronesian Realm (North Atlantic Ocean)
- in: R. Riosmena-Rodríguez, W. Nelson, J. Aguirre (Eds.), Rhodolith/Maërl Beds: A Global Perspective, Vol. 15, Coastal Research Library (2017), pp. 221–261
-

12.

- Kobayashi, 2006
- D.R. Kobayashi
- Colonization of the Hawaiian Archipelago via Johnston Atoll: a characterization of oceanographic transport corridors for pelagic larvae using computer simulation
- Coral Reefs, 25 (2006), pp. 407–417
-

13.

- Ladd and Hoffmeister, 1945
- H.S. Ladd, J.E. Hoffmeister

- Geology of Lau, Fiji
- Bishop Museum Bull, 181 (1945), pp. 1–399
-

14.
- Leitão and Alvarez, 2011
- H. Leitão, W. Alvarez
- The Portuguese and Spanish voyages of discovery and the early history of geology
- Geol. Soc. Am. Bull., 123 (2011), pp. 1219–1233
-

15.
- Malay and Michonneau, 2014
- M.C.M.D. Malay, F. Michonneau
- Phylogenetics and morphological evolution of coral-dwelling barnacles (Balanomorpha: Pyrgomatidae)
- Biol. Jour Linnaean Soc., 113 (2014), pp. 162–179
-

16.
- McBirney and Williams, 1969
- A.R. McBirney, H. Williams
- Geology and petrology of the Galápagos Islands
- Geol Soc Am Mem, 118 (1969) (197 p)
-

17.
- McMurtry et al., 2010
- G.M.N. McMurtry, J.F. Campbell, G.J. Fryer, J. Fietzke
- Uplift of Oahu, Hawaii, during the past 500 ky as recorded by elevated reef deposits
- Geology, 38 (2010), pp. 27–30
-

18.
- McNutt and Menard, 1978
- M. McNutt, H.W. Menard
- Lithosperic flexture and uplifted atools
- J Geophy Res., 83 (1978), pp. 1206–1212
-

19.
- Ménabréaz et al., 2010
- L. Ménabréaz, N. Thouveny, G. Camoin, S.P. Lund
- Paleomagnetic record of the late Pleistocene reef sequence of Tahiti (French Polynesia): a contribution to the chronology of the deposits
- Earth and Planetary Sci Letters, 294 (2010), pp. 58–68
-

20.
- Menard, 1986
- H.W. Menard

- Islands
- Scientific American Library, New York (1986) (230 p)
-

1.
- Menard et al., 1962
- H.W. Menard, E.C. Allison, J.W. Durham
- A drowned Miocene terrace in the Hawaiian islands
- Science, 138 (1962), pp. 896–897
-

2.
- Montaggioni, 1982
- L.F. Montaggioni
- Pleistocene marine depositional environments from Mauritius Island, Indian Ocean
- Geobios, 15 (1982), pp. 161–179
-

3.
- Montaggioni et al., 1985
- L.F. Montaggioni, G. Richard, F. Bourrouilh-Le Jan, C. Gabrié, L. Humbert, M. Monteforte, O. Naim, C. Payri, B. Salvat
- Geology and marine biology of Makatea, an uplifted atoll, Tuamotu Archipelago, Central Pacific Ocean
- J. Coastal Res., 1 (1985), pp. 165–171
-

4.
- Moyse, 1971
- J. Moyse
- Settlement and growth pattern of the parasitic barnacle Pyrgoma anglicum
- D.J. Crisp (Ed.), Fourth European Biology Symposium, Cambridge University Press, London (1971), pp. 125–142 (599 p)
-

5.
- Muhs and Szabo, 1994
- D.R. Muhs, B.J. Szabo
- New uranium-series ages of the Waimanalo Limestone, Oahu, Hawaii: implications for sea level during the last interglacial period
- Mar. Geol., 118 (1994), pp. 315–326
-

6.
- Muhs et al., 2002
- D.R. Muhs, K.R. Simmons, B. Steinke
- Timing and warmth of the last interglacial period: new U-series evidence from Hawaii and Bermuda and a new fossil compilation for North America
- Quat. Sci. Rev., 21 (2002), pp. 1355–1383
-

7.
- Muhs et al., 2014
- D.R. Muhs, J. Meco, K.R. Simmons
- Uranium-series ages of corals, sea level history, and palaeozoogeography, Canary Islands, Spain: an exploratory study for two quaternary interglacial periods
- Palaeogeog, Palaeoclim Palaeoecol, 394 (2014), pp. 99–118
-

8.
- Newman and Ross, 1976
- W.A. Newman, A. Ross
- Revision of the balanomorph barnacles; including a catalog of the species
- Mem. San Diego Soc. Nat. Hist., 9 (1976), pp. 1–108
-

9.
- Nielson and Sibbett, 1996
- D.L. Nielson, B.S. Sibbett
- Geology of Ascension Island, South Atlantic Ocean
- Geothermics, 25 (1996), pp. 427–448
-

10.
- Nunes et al., 2010
- J.C. Nunes, E.A. Lima, M.P. Costa, A. Porteiro
- Azores Islands volcanism and volcanic landscapes: its contribution to the geotourism and the Azores Geopark Project
- Geosci. Onlline J., 18 (16) (2010) (4 p)
-

11.
- Nunn, 1996
- P.D. Nunn
- Emerged shorelines of the Lau Islands. Fiji Gov. mineral resources department
- Memoir, 5 (1996), pp. 1–97
-

12.
- Nunn and Omura, 1999
- P.D. Nunn, A. Omura
- Penultimate interglacial emerged reef around Kadavu Island, sosjuthwest Pacific: implicaltions for late Quaternary island-arc tectonics and sea-level history
- New Zealand J. Geol. Geophys., 42 (1999), pp. 219–227
-

13.
- Ogawa and Matsuzaki, 1992
- K. Ogawa, K. Matsuzaki
- An essay on host specificity, systematic taxonomy, and evolution of the coralbarnacles
- Bull Biogeograph. Soc. Japan, 47 (1992), pp. 87–101
-

14.
- Olsen, 1975
- S.L. Olsen
- Paleornithology of St. Helena Island, South Atlantic Ocean. Smithsonian Contributions to Paleobiology Number 23
- (1975) (59 p)
-

15.
- Pearson and Nicholas, 2007
- P.N. Pearson, C.J. Nicholas
- 'Marks of extreme violence': Charles Darwin's geological observations at St Jago (São Tiago), Cape Verde islands
- in: P.N. Wyse Jackson (Ed.), Four Centuries of Geological Travel: The Search for Knowledge on Foot, Bicycle, Sledge and Camel, Vol. 287, Geol Soc London Spec Pub (2007), pp. 239–253
-

16.
- Perrin and Bosellini, 2012
- C. Perrin, F.R. Bosellini
- Paleobiogeography of scleractinian reef corals: changing patterns during the Oligocene-Miocene climatic transition in the Mediterranean
- Earth-Sci. Rev., 111 (2012), pp. 1–24
-

17.
- Railsback et al., 2015
- L.B. Railsback, P.L. Gibbard, M.J. Head, N. Riavo, G. Voarintsoa, S. Toucanne
- An optimized scheme of lettered marine isotope substates for the last 1.0 million years, and the climatostraigrahic nature of isotope states and substages
- Quat. Sci. Rev., 111 (2015), pp. 94–106
-

18.
- Ramalho et al., 2010
- R.S. Ramalho, G. Helffrich, M. Cosca, D. Vance, D. Hofmann, D.N. Schmidt
- Episodic swell growth inferred from variable uplift of the Cape Verde hotspot islands
- Nat. Geosci., 3 (2010), pp. 774–777
-

19.
- Ramalho et al., 2013
- R.S. Ramalho, R. Quartau, A.S. Trenhaile, N.C. Mitchell, C.D. Woodroffe, S.P. Ávila
- Coastal evolution on volcanic oceanic islands: a complex interplay between volcanisms, erosion, sedimentation sea-level change and biogenic production
- Earth Sci. Rev., 127 (2013), pp. 140–170
-

20.

- Ramalho et al., 2015
- R.S. Ramalho, A.B. Da Silveira, P.E. Fonseca, J. Madeira, M. Cosca, M. Cachão, M.M. Fonseca, S.N. Prada
- The emergence of volcanic oceanic islands on a slow-moving plate: the example of Madeira Island, NE Atlantic
- Geochem. Geophys. Geosyst., 16 (2015), pp. 522–537
-

1.
- Ramalho et al., 2017
- R.S. Ramalho, G. Helffrich, J. Madeira, M. Cosca, C. Thomas, R. Quartau, A. Hipólito, A. Rovere, P.J. Hearty, S.P. Ávila
- Emergence and evolution of Santa Maria Island (Azores) – the conundrum of uplifted islands revisited
- Geol. Soc. Am. Bulletin, 129 (2017), pp. 372–391
- View Record in Scopus

  |

  Citing articles (9)

2.
- Rebelo et al., 2014
- A.C. Rebelo, M.W. Rasser, R. Riosmena-Rodríguez, A.I. Neto, S.P. Ávila
- Rhodolith forming coralline algae in the Upper Miocene of Santa Maria Island (Azores, NE Atlantic): a taxonical study
- in: R. Riosmena-Rodíguez, G.W. Maneveldt, P. Horta, M. Figueiredo (Eds.), Systematics and Biogeography of the Subclass Corallilnophycideae (Rhodophyta) from the Atlantic Ocean. Phytotaxa, 190, (2014), pp. 370–382
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (9)

3.
- Rebelo et al., 2016
- A.C. Rebelo, M.W. Rasser, A. Kroh, M.E. Johnson, R.S. Ramalho, C. Melo, A. Uchman, B. Berning, L. Silva, V. Zannon, A. Neto, M. Cachao, S.P. Ávila
- Rocking around a volcanic island shelf: Pliocene rhodolith beds from Malbusca, Santa Maria Island (Azores, NE Atlantic)
- Facies, 62 (2016), pp. 1–31

- View Record in Scopus

  |

  Citing articles (1)

4.
- Redman et al., 2007
- C.M. Redman, L.R. Leighton, S.A. Schellenberg, C.N. Gale, J.L. Nielsen, D.L. Dressler, M.K. Klinger
- Influence of spatiotemporal scale on the interpretation of paleocommunity structure: lateral variation in the imperial formation of California
- PALAIOS, 22 (2007), pp. 630–641
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (19)

5.
- Ross and Newman, 2002
- A. Ross, W.A. Newman
- Coral barnacles: Cenozoic decline and extinction in the Atlantic/East Pacific versus diversification in the Indo-West Pacific
- in: M.K. Kasim Moosa, S. Soemodihardjo, A. Nontiji, A. Soegiarto, K. Romimohtarto, Sukarno, Suharsona (Eds.), Proceedings 9th International Coral Reef Symposium, Bali, Indonesia, 1, (2002), pp. 179–184
- View Record in Scopus

  |

  Citing articles (14)

6.
- Santos et al., 2012
- A. Santos, E. Mayoral, G.B. Baarli, C.M. Da Silva, M. Cachão, M.E. Johnson
- Symbiotic association of a Pyrgomatid barnacle with a coral from a volcanic middle Miocene shoreline (Porto Santo, Madeira Archipelago, Portugal)
- Palaeontology, 55 (2012), pp. 173–182
- CrossRef

  |

View Record in Scopus

|

Citing articles (8)

7.
- Scott and Rotondo, 1983
- G.A.J. Scott, G.M. Rotondo
- A model to explain the differences between Pacific Plate island-atoll types
- Coral Reefs, 1 (1983), pp. 139–150
- CrossRef

|

View Record in Scopus

|

Citing articles (42)

8.
- Self, 1976
- S. Self
- The recent volcanology of Terceira, Azores
- J. Geol. Soc. Lond., 132 (1976), pp. 645–666
- CrossRef

|

View Record in Scopus

|

Citing articles (63)

9.
- Stehli, 1968
- F. Stehli
- Taxonomic diversity gradients in pole locations: The Recent model
- E.T. Drake (Ed.), Evolution and Environment, Yale Univ Press, New Haven (1968), pp. 163–227 (470 p)
-

10.
- Stein and Stein, 1992
- C.A. Stein, S. Stein

- A model for the global variation in oceanic depth and heat flow with lithospheric age
- Nature, 359 (6391) (1992), p. 123
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (861)

11.
- Stott, 2003
- R. Stott
- Darwin and the Barnacle: The Story of one Tiny Creature and History's Most Spectacular Scientific Breakthrough
- W.W. Norton & Co, New York (2003) (256 p)
-

12.
- Tappin and Balance, 1994
- D.R. Tappin, P.F. Balance
- Contributions to the sedimentary geology of Eua Island, Kingdom of Tonga
- in: A.J. Stevenson, R.H. Herzer, R.F. Balance (Eds.), Geology and submarine resources of the Tonga-Lau-Fiji Region, vol. 8, S Pac Appl Geos Commission Tech Bull (1994), pp. 1–21
-

13.
- Tappin et al., 1996
- D.R. Tappin, R.H. Herzer, A.J. Stevenson
- Structure and history of an oceanic forearc - The Tonga Ridge - 22° to 26° South
- in: A.J. Stevenson, R.H. Herzer, P.F. Balance (Eds.), Geology and Submarine Resources of the Tonga–Lau–Fiji Region, vol. 8, S Pac Appl Geos Commission Tech Bull (1996), pp. 81–100
-

14.
- Teixeira et al., 2003
- W. Teixeira, U.G. Cordani, E.A. Menor, M.G. Teixeira, R. Linsker
- Arquipélago Fernando de Noronha: O Paraíso do Vulcão
- Terra Virgem, São Paulo (2003) (167 p)
-

15.
- Thomas et al., 2009
- A.L. Thomas, G.M. Henderson, P. Deschamps, Y. Yokoyama, A.J. Mason, E. Bard, B. Hamelin, N. Durand, G. Camoin

- Penultimate deglacial sea-level timing from uranium/thorium dating of Tahitian corals
- Science, 324 (2009), pp. 1186–1189
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (78)

16.
- Toomey et al., 2013
- M. Toomey, A.D. Ashton, J.T. Perron
- Profiles of ocean island coral reefs controlled by sea-level history and carbonate accumulation rates
- Geology, 41 (2013), pp. 731–734
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (17)

17.
- Van Andel et al., 1973
- T.H. Van Andel, D.K. Rea, R.P. Von Herzen, H. Hoskins
- Ascension fracture zone, Ascension Island, and the Mid-Atlantic Ridge
- Geol. Soc. America Bull, 84 (1973), pp. 1527–1546
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (36)

18.
- Vermeij, 2012

- G.J. Vermeij
- The tropical history and future of the Mediterranean biota and the West African enigma
- J. Biogeogr., 39 (2012), pp. 31–41
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (18)

19.
- Veron, 1995
- J.E.N. Veron
- Corals in space and time: the biogeography and evolution of the scleractinia
- Comstock/Cornell, Ithaca (1995) (321 p)
-

20.
- Vertino et al., 2014
- A. Vertino, J. Stolarski, F.R. Bosellini, M. Faviani
- Mediterranean corals through time: from Miocene to Present
- , The Mediterranean Sea, Springer, Netherlands (2014), pp. 257–274
- CrossRef

  |

  View Record in Scopus

  |

  Citing articles (16)

1.
- Viola and Margolis, 1985
- H.J. Viola, C. Margolis
- Magnificent Voyagers: The U.S
- , Exploring Expedition, Vols. 1838-1842, Smithsonian Institution, Washington, D.C. (1985), p. 268
-

2.
- Vogt and Jung, 2007
- R.P. Vogt, W.Y. Jung

- Origin of the Bermuda volcanoes and the Bermuda Rise: history, observations, models, and puzzles
- , Geol Soc Am Spec Pap 430, (2007), pp. 553–591
-

3.
- Woodroffe, 2014
- C.D. Woodroffe
- The rock coasts of oceanic islands
- D.M. Kennedy, W.J. Stephenson, L.A. Naylor (Eds.), Rock Coast Geomorphology: A Global Synthesis, Geol Soc Lond Memoirs 40 (2014), pp. 247–261
-

4.
- Woodroffe et al., 1991
- C.D. Woodroffe, H.H. Veeh, A.C. Falkland, R.F. McLean, E. Wallensky
- Last interglacial reef and subsidence of the Cocos (Keeling) Islands, Indian Ocean
- Mar. Geol., 96 (1991), pp. 137–143
-

5.
- Woodroffe et al., 1999
- C.D. Woodroffe, R.F. McLean, S.G. Smithers, E.M. Lawson
- Atoll reef-island formation and response to sea-level change: West Island, Cocos (Keeling) Island
- Mar. Geol., 160 (1999), pp. 85–104
-

6.
- Zaczek et al., 2015
- K. Zaczek, V.R. Troll, M. Cachão, J. Ferreira, F.M.N. Deegan, J.C. Carracedo, V. Soler, F.C. Meade, S. Burchardt
- Nannofossils in 2011 Eirro eruptive products reinstate plume model for Canary Islands. Scientific reports
- , Nature (2015) 5 p https://doi.org/10.1038/srep07945
-

7.
- Zazo et al., 2007
- C. Zazo, J.L. Goy, C.J. Dabrio, V. Soler, C. Hillaire-Marcel, B. Ghaleb, J.A. González-Delgado, T. Bardají, A. Cabero
- Quaternary marine terraces on Sal Island (Cape Verce archipelago)
- Quat. Sci. Rev., 26 (2007), pp. 876–893
-

8.
- Zazo et al., 2010
- C. Zazo, J.L. Goy, C. Hillaire-Marcel, C.J. Dabrio, J.A. González, A. Cabero, T. Bardají, B. Ghaleb, V. Soler
- Sea level changes during the last and present interglacials in Sal Island (Cape Verde archipelago)

- Global and Plenary Change, 72 (2010), pp. 302–317
-

Corresponding author.